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ABSTRACT

This first in a series of six modules for a course titled Nondestructive Examination (NDE) Techniques II introduces the student/trainee to the basic behavior of ultrasound, describes ultrasonic test equipment, and outlines the principal methods of ultrasonic testing. The module follows a typical format that includes the following sections: (1) introduction, (2) module prerequisites, (3) objectives, (4) notes to instructor/student, (5) subject matter, (6) materials needed, (7) procedures, (8) data table, (9) reference materials, (10) test. (The course is one of fifteen technical courses for the second year of a two-year postsecondary curriculum in Nuclear Quality Assurance/Quality Control Technology.) (LRA)

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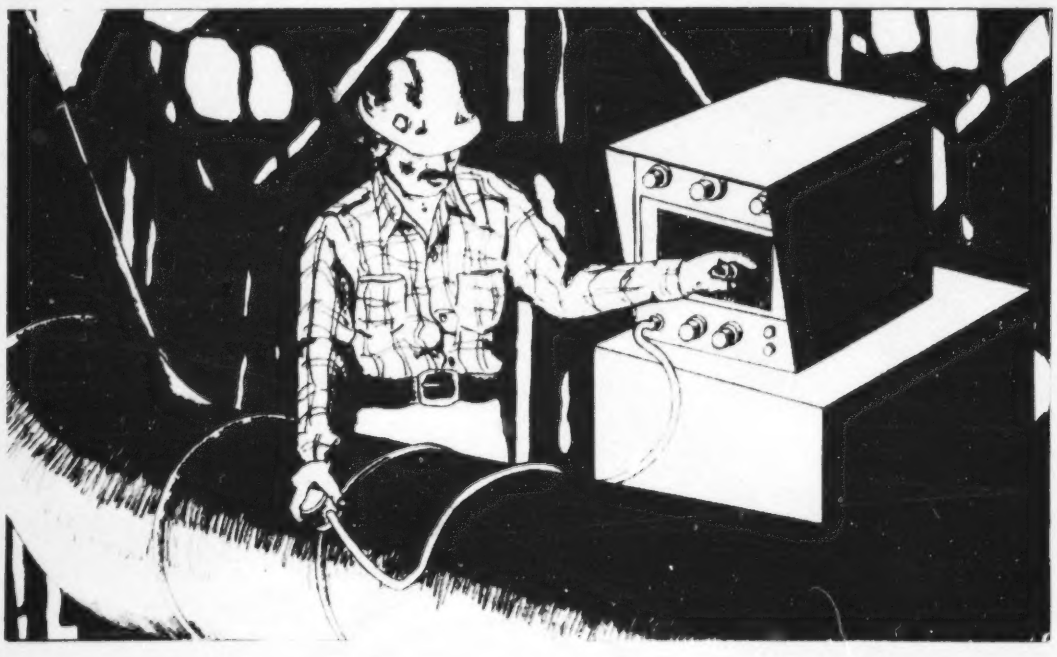
NUCLEAR TECHNOLOGY

COURSE 32 NONDESTRUCTIVE EXAMINATION (NDE) TECHNIQUES II

MODULE 32-1 Fundamentals of Ultrasonic Testing



CE 024 293

GENERAL PHYSICS CORPORATION
Columbia , Maryland

COURSE MODULES

COURSE 32 NONDESTRUCTIVE EXAMINATION (NDE) TECHNIQUES II

Module 32-1	Fundamentals of Ultrasonic Testing
Module 32-2	Operation of Ultrasonic Test Equipment
Module 32-3	Fundamentals of Magnetic Particle Testing
Module 32-4	Operation of Magnetic Particle Test Equipment
Module 32-5	Fundamentals of Eddy Current Testing
Module 32-6	Operation of Eddy Current Test Equipment

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This module was prepared for General Physics Corporation by Bruce Spaulding, General Physics Corporation.

GENERAL PHYSICS CORPORATION

1979

INTRODUCTION

The Nuclear QA/QC Technician may qualify as an ultrasonic test inspector or may have responsibility for reviewing ultrasonic inspection reports. In these capacities, the technician must be familiar with theory, equipment, test techniques, and acceptance criteria associated with ultrasonic inspection.

Ultrasonic Testing is a nondestructive technique for the examination of materials and products utilizing the transmission of high frequency sound waves, also known as ultrasound, in the test material. This is in contrast to radiographic inspection which uses either x-rays or gamma rays. Both ultrasonic testing and radiography are volumetric inspection methods. That is, the entire volume of material can be examined with these methods.

This module introduces the student/trainee to the basic behavior of ultrasound, describes ultrasonic test equipment, and outlines the principal methods of ultrasonic testing. The immediate purpose of this module is to prepare the student/trainee for the second ultrasonic module which details specific testing techniques (Module 32-2, Course 32). This module and Module 32-2 are intended to prepare the student/trainee for the American Society for Nondestructive Testing's Level II Certification Test for Ultrasonic Testing.

MODULE PREREQUISITES

Course 26, Nondestructive Examination Techniques I should have been completed before proceeding to this course.

OBJECTIVES

Upon completion of this module, the student/trainee can:

1. Define the following terms:
   - wavelength
   - period
   - frequency
   - velocity
   - acoustic impedance
   - reflection
   - refraction
   - longitudinal wave
   - transverse wave
   - surface wave
2. Identify and describe the following components and their functions for a typical ultrasonic test setup: probe, signal generator, receiver, cathode ray tube, amplifier, clock, and power supply.
3. Identify the type and purpose of an ultrasonic test given a schematic diagram of the test setup.
4. Identify, and briefly describe, the test method which would accomplish a stated test requirement.
5. Name the four (4) basic wave modes discussed in this module and describe each.
6. Name the four (4) classes of ultrasonic test and describe each.
7. Name the three (3) types of pulse-echo test and distinguish between them.

NOTES TO INSTRUCTOR / STUDENT

This module introduces the student/trainee to the basic behavior of ultrasound, describes ultrasonic test equipment, and outlines the principal methods of ultrasonic testing. This material is intended to prepare the student/trainee for the American Society for Nondestructive Listings Level II Certification Test for Ultrasonic Testing.

Every attempt has been made in preparing this module to deal with the principles of ultrasound so that the student/trainee with a moderate knowledge of physics and mathematics can understand this important nondestructive examination technique. Although there are no stated prerequisites for this module, a brief review of electronic principles along with fundamentals of trigonometry may be useful for better understanding of this material.

PRINCIPLES OF ULTRASONIC WAVE BEHAVIOR

Oscillations and Waves

The ultrasonic testing of materials makes use of mechanical vibrations or oscillations of the atoms in matter to conduct the tests. These oscillations travel as waves and by measuring and analyzing the behavior of the waves in the test material, much can be learned about the structure of the material.

To understand ultrasonic testing, therefore, we should first look at waves. What are waves? It is best, perhaps, to first look at examples of waves. Consider what happens when a small stone is dropped into a smooth pond. A circular pattern spreads out from the point at which the stone hit the water. Such a moving disturbance is a wave. It is important to realize that what is actually moving is the disturbance, and not the water itself. This can be clearly seen if you watch something floating in the water, such as a small chip of wood or a fishing line float. The chip or float merely moves up and down or oscillates vertically as the wave passes; it does not move horizontally with the wave. The wave, or disturbance has travelled through the water, but the water itself has not moved with the wave.

A second example of how a wave moves in a material is the rippling of a flag in the breeze. The rippling of the flag is actually the travelling of waves along its length. Obviously, the individual points on the flag remain fixed with respect to each other as the ripples move along the flag's length. The stripes on the American flag don't get longer or shorter and the stars don't move around on the field. Just as the water in the pond does not move with the wave, the cloth of the flag is the same as before

and after passage of the wave.

The travelling of a wave is referred to as propagation. When water travels outwardly, it is common to say that it propagates outwardly. Similarly, reference to the travel of a sound wave is by stating the direction of propagation.

The speed with which a wave travels in its direction of propagation is its velocity.

Waves can be either periodic or non-periodic. A periodic wave is one in which the motion of the material repeats itself over and over in a regular pattern over time. A non-periodic wave is one in which the repetition is not regular or there is no repetition at all. A very important type of periodic wave is the very short burst of periodic waves called a pulse. Hereafter, unless stated otherwise, wave means periodic wave.

Wave Parameters

There are three basic parameters of a wave that must be defined and related to each other: wavelength, velocity, and frequency. The parts of a wave are first reviewed to permit definition of these parameters.

For a surface wave, such as the pond waves and illustrated in Figure 32-1-1, the highest point of the wave is the crest. The lowest point is the trough. The vertical distance from the equilibrium position to the crest or the trough (those distances are equal) is the amplitude of the wave. The cycle of a wave is one complete "turn" of the wave, from crest to crest, for example.

The distance between successive crests or troughs or other corresponding points in a wave is defined as the wavelength, which is usually referred to by the Greek letter lambda (λ). The time it takes a length of a propagating wave equal to one wavelength (1λ) to pass a given point in space is defined as the period, which is frequently

referred to by the letter T, although the Greek letter tau (τ) is sometimes used. The number of wavelengths (or crests, or troughs) passing a given point per unit time is defined as the frequency, which is frequently referred to by the letter f, although the Greek letter nu (ν) is sometimes used.

Since frequency is cycles per unit time and period is time per cycle, each is the reciprocal of the other:

$$f = \frac{1}{T} \qquad \text{Equation 32-1-1}$$

Where:

f = frequency

T = period

For ultrasonic testing, frequency is the preferred way to describe how rapidly a wave oscillates and the most common units used are megacycles per second or megahertz (1 Hertz ≡ 1 cycle per second). The abbreviation for megahertz is MHz.

If wavelength is divided by period, the quotient is length divided by time which is velocity, referred to by a lower case c; but more frequently, v outside of ultrasonic testing.

$$c = \frac{\lambda}{T} \qquad \text{Equation 32-1-2}$$

Where:

c = velocity

λ = wavelength

T = period

But Since:

$$f = \frac{1}{T}$$

Then:

$c = \lambda f$ Equation 32-1-3

Where:

c = velocity

λ = wavelength

f = frequency

EXAMPLE

Problem: Find the wavelength of an ultrasonic pulse in steel.

Given: The wave has a frequency of 2.0 MHz and is propagating at 5900 m/sec.

Solution:

$$\lambda = \frac{c}{f} = \frac{5.9\ (10)^3\ \frac{m}{sec}}{2.0\ (10)^6\ \frac{1}{sec}}$$ (Variation of Equation 32-1-3)

$$\lambda = 2.95\ (10)^{-3} m$$

or $\lambda = 2.95$ mm

Notice in the foregoing example that wavelength is inversely proportional to frequency. As frequency increases, wavelength decreases. Because wavelength is important to the interaction of sound and materials, wavelength can be tailored by adjusting frequency to obtain optimum results in ultrasonic testing.

Wave Modes

There are three basic kinds or modes of waves: longitudinal, transverse, and torsional, but only longitudinal and transverse are discussed here. A transverse wave is a wave whose oscillations are perpendicular to its direction of propagation. Examples of transverse waves include water surface waves, guitar strings, and light.

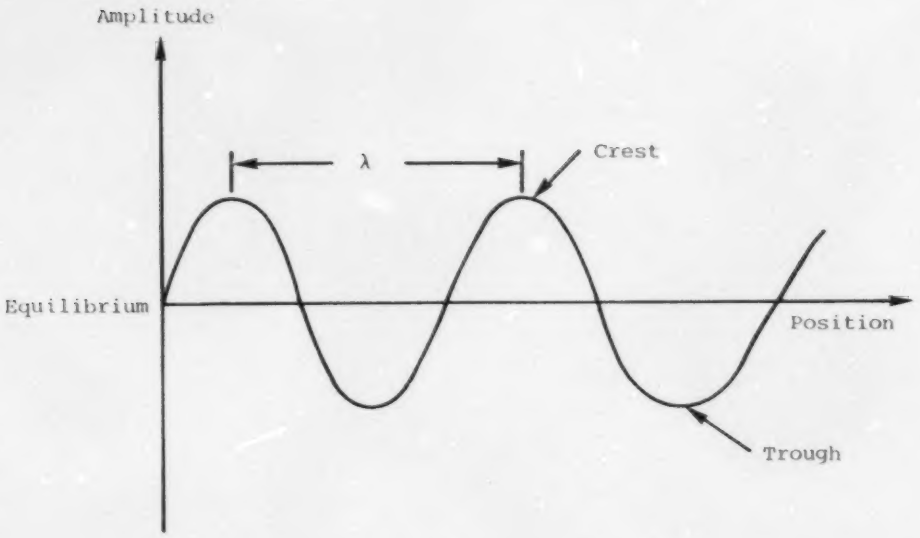


Figure 32-1-1. Surface Wave

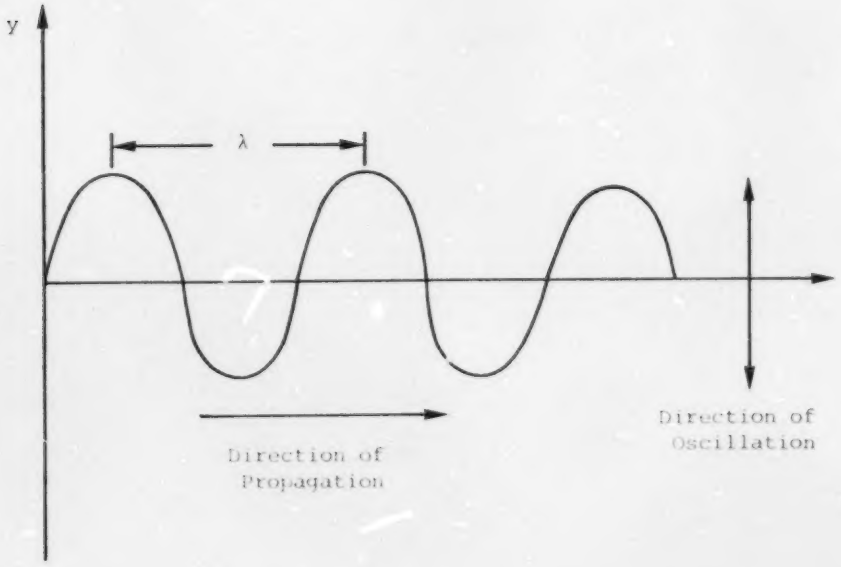


Figure 32-1-2. Transverse Wave

A transverse wave is shown schematically in Figure 32-1-2. In ultrasonic testing, transverse waves are quite frequently referred to as shear waves, because the generating mechanism exerts a periodical shear force on the material.

A longitudinal wave is a wave whose oscillations are parallel to its direction of propagation. Examples of longitudinal waves include sound waves in gases and liquids and the rippling of grain stalks by the wind as referred to in "...amber waves of grain...". A longitudinal wave is shown schematically in Figure 32-1-3 below.

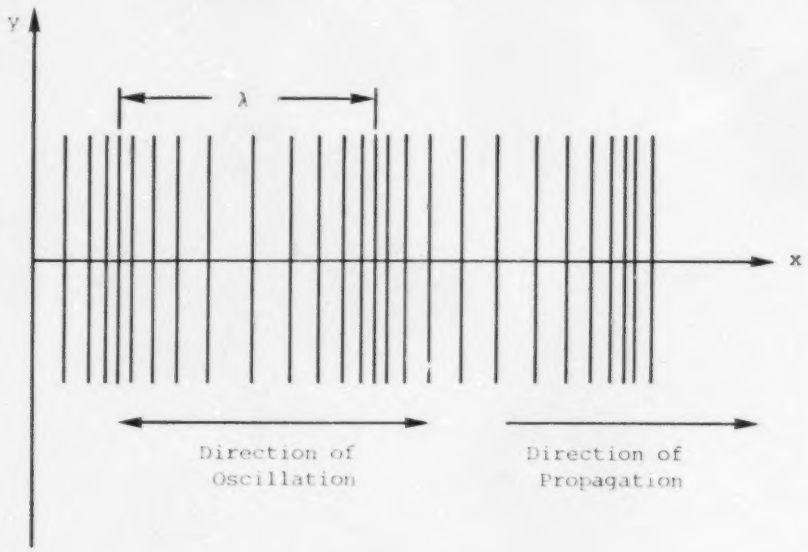


Figure 32-1-3. Longitudinal Wave

Two other classes of waves are important in ultrasonic testing: surface waves and plate waves. What is different is that up until now, only waves in an infinite medium have been considered. Surface and plate waves are merely special cases where the basic transverse mode acts at or near boundries.

The surface or Rayleigh wave propagates on the boundary surface of a metal interfacing with a gas, if the metal

is relatively thick. Relatively thick means significantly larger than one wavelength, as that is typically the depth at which particles are only slightly excited by the wave. Figure 32-1-4 illustrates the motion of the top layer of particles in a metal that is undergoing surface wave deformation. As can be seen, this deformation is not sinusoidal.

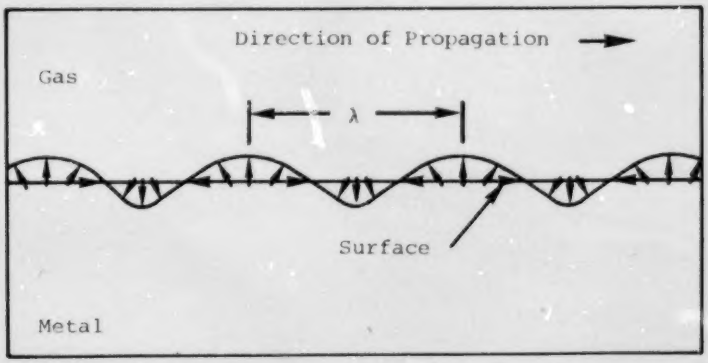


Figure 32-1-4. Surface or Rayleigh Wave

Surface waves propagate along the flat or curved surfaces of a metal at a velocity equal to approximately 90% of a transverse wave in the interior of the same material. Upon hitting a discontinuity in a surface, such as sharp corners, the surface wave is reflected. Thus, ultrasonic surface waves can be used to test very complex surfaces quite simply.

If the metal is not significantly thicker than one wavelength of a surface wave on that material, then the entire plate can oscillate in any of several modes. The two types important in ultrasonic testing are known as Lamb waves. The schematic representations in Figure 32-1-5 illustrate the two basic forms of Lamb wave. Limited use of Lamb waves is used in ultrasonic testing as compared to transverse, longitudinal, and surface waves.

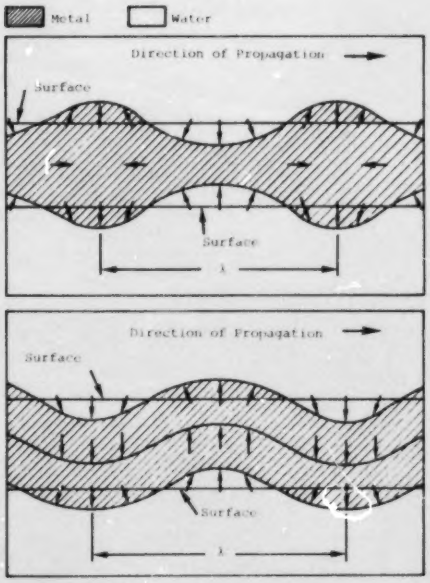


Figure 32-1-5. Plate or Lamb Waves

Sound and Ultrasound

Sound and ultrasound are both oscillations in a material. The only difference is that ordinary or audible sound has a frequency below 20 kHz (20,000 Hz), which is the upper threshold of human hearing, and ultrasound has a frequency above 20 kHz. The ultrasound used in materials testing usually is far higher in frequency than this somewhat arbitrary value of 20 kHz. In fact, its frequency is usually between 200 kHz and 16 MHz.

In referring to oscillations in a material, what is actually oscillating? Since ultrasonic testing described herein is concerned with testing of solids, only solids are closely examined. The structure of a solid can be fairly accurately modelled by imagining it to be composed of small particles, called atoms or ions, held together by springs. (See Figure 32-1-6. The spring connections allow the atoms to move about their equilibrium positions but constrains them from moving too far out of position. If an

impulse is provided to one particle, it moves, exerting forces on the particles around it. These other particles then move, and in turn, exert forces on the particles around them, thus causing the initial disturbance to propagate as a wave. Of course, the springs only represent the elastic bonds between the atoms.

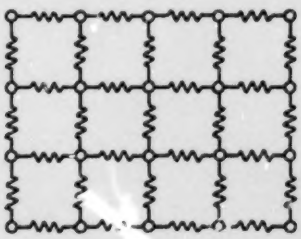


Figure 32-1-6. Model of a Solid

If the particles along a plane in a material are caused to move vertically to the plane, their connections to the adjacent plane of particles cause the second plane to move also. The second plane in turn causes the third to move which causes the fourth to move, and so on. Such oscillation is in the direction of propagation which makes this a longitudinal wave. Because of the pressing together of the planes of atoms, this is also known as a pressure or a compressional wave. In Figure 32-1-7, a longitudinal wave in matter is depicted. The "crests" are those places where the atoms are most tightly packed and the "troughs" are those places where the atoms are least tightly packed.

The speed of the longitudinal wave in matter is referred to as the velocity of sound of the longitudinal wave, written as C_ℓ. This velocity is a material dependent parameter, that is, it changes with the material, but is

essentially constant within a given homogeneous material. For selected materials important to the ultrasonic test procedures in the nuclear industry, the velocities of sound of the longitudinal wave are as listed in Table 32-1-1.

Table 32-1-1. Longitudinal Sonic Velocities

Steel	C_ℓ = 5900 m/sec
Aluminum	C_ℓ = 6300 m/sec
Water	C_ℓ = 1480 m/sec

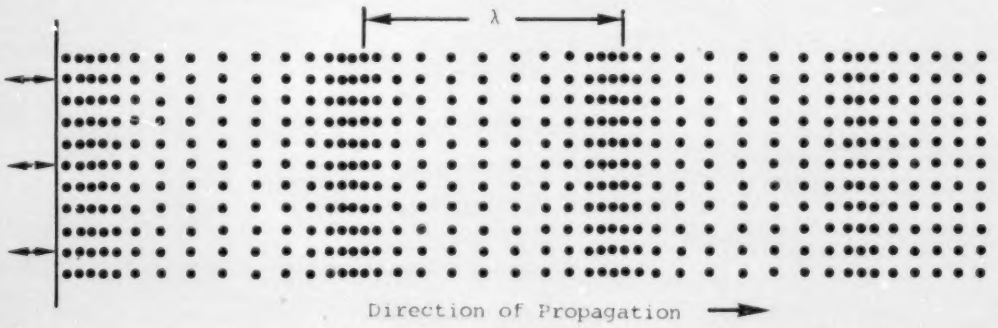


Figure 32-1-7. Longitudinal Wave in a Solid

Because of the values of sound velocities in steel and aluminum, it is convenient to state wavelengths in mm, frequency in MHz, and velocity in km/sec. The convenience of this approach is apparent in the following example

EXAMPLE

Problem: Find the wavelength of a longitudinal wave in steel and aluminum.

Given: Frequency in steel is 1MHz and in aluminum is 5MHz.

Solution:

(a) Steel: $\lambda_{St} = \frac{C_\ell}{f} = \frac{5.9 \text{ km/sec}}{1.0 \text{ MHz}} = 5.9 \text{ mm}$

(b) Aluminum: $\lambda_{Al} = \frac{C_\ell}{f} = \frac{6.2 \text{ km/sec}}{5 \text{ MHz}} = 1.2 \text{ mm}$

If the particles along a plane in a material are caused to move parallel to the plane, the resulting wave is a transverse wave. In Figure 32-1-8, a transverse wave in solid matter is depicted. Since shearing forces can not be transmitted in a gas or a liquid, transverse waves are only possible in a solid.

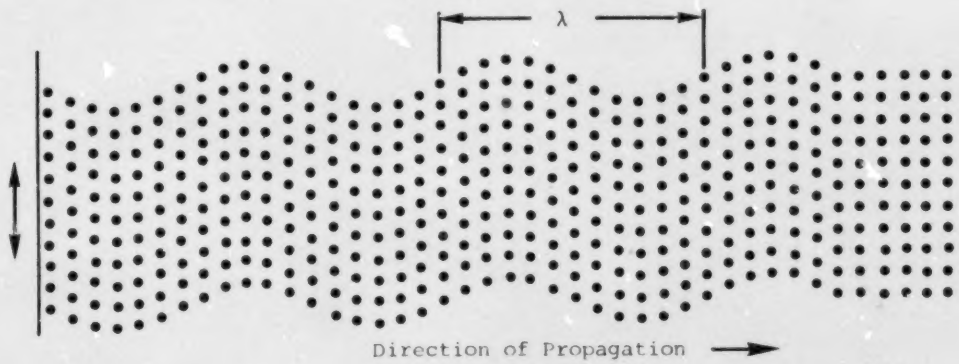


Figure 32-1-8. Transverse Wave in a Solid

The speed of the transverse wave in a solid material is referred to as the velocity of sound of the transverse wave. The transverse velocities of sound in materials of interest are listed in Table 32-1-2.

Table 32-1-2. Transverse Sonic Velocities

Material	Velocity
Steel:	C_t = 3230 m/sec
Aluminum:	C_t = 3130 m/sec
Water:	None

EXAMPLE

Problem: Find the wavelength of a transverse wave in steel and in aluminum.

Given: Frequency in steel is 1MHz and in aluminum is 5MHz.

Solution:

(a) Steel $\lambda_{st} = \frac{C_t}{f} = \frac{3.23 \text{ km/sec}}{1.00 \text{ MHz}} = 3.23 \text{ mm}$

(b) Aluminum: $\lambda_{al} = \frac{C_t}{f} = \frac{3.13 \text{ km/sec}}{5.00 \text{ MHz}} = 0.62\text{mm}$

Reflection and Refraction

When waves strike a surface or interface between materials, they are either reflected or transmitted, or both. Reflection occurs when propagating waves hit a smooth flat surface and some or all of the incident (incoming) wave is reflected. The percentage reflected depends upon the nature of the materials and the angle between the wave and the surface. The angle of incidence is measured between the perpendicular to the wave front, hereinafter called the ray, and the perpendicular to the surface, hereinafter called the normal. The angle of reflection is measured between the normal and the perpendicular to the reflected wave front.

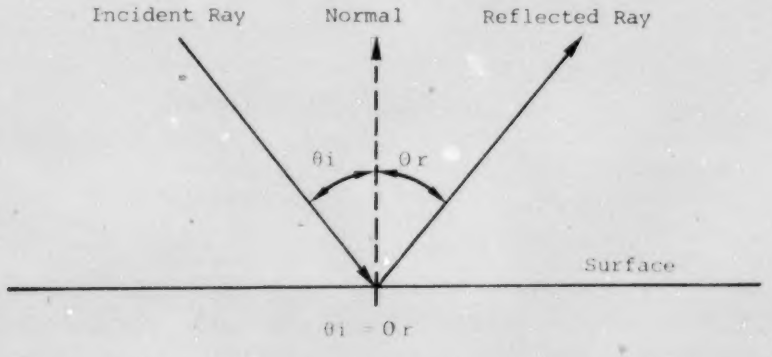


Figure 32-1-9. Reflection

$$\theta_i = \theta_r$$ Equation 32-1-4

Where:

θ_i = Angle of incidence

θ_r = Angle of reflection

When a ray hits an interface between materials, some of it may be transmitted. The transmitted portion will usually bend, or travel in a different direction in the second material. This process of bending is refraction and the amount of bending is related to the ratio of velocities in the materials.

Snell's Law permits calculation of angle of refraction by Equation 32-1-5. The applicable form of Snell's Law is slightly different than its original form which is used in optics. The reason for the difference is that in ultrasonics there is no "ultimate" wave velocity comparable to the speed of light in a vacuum for optics.

$$\frac{\sin \theta_i}{\sin \theta_R} = \frac{C_1}{C_2}$$ Equation 32-1-5

Where:

θ_i = Angle of incidence

θ_R = Angle of refraction

C_1 = Sound velocity in medium 1

C_2 = Sound velocity in medium 2

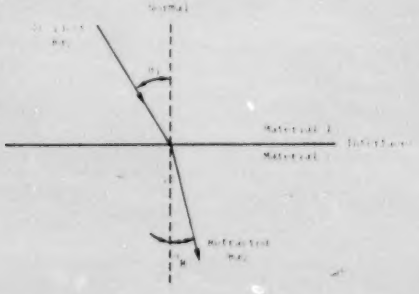


Figure 32-1-10 Refraction

There are several consequences of Snell's Law that are of great importance to ultrasonic testing. First, because longitudinal and transverse waves propagate at different angles. Second, when a wave is incident upon a surface from a normal direction (i.e., $\theta_i = 0^o$), the transmitted ray is undeviated from the incident ray (i.e., $\theta_R = 0^o$) Third, when an incident longitudinal wave is refracted upon entry into the second material, the incident ray is split into a longitudinal wave (L-wave) and a transverse wave (S-wave). (See Figure 32-1-11.)
Fourth, there are certain critical angles beyond which waves are completely reflected when passing into a medium where the velocity of sound is higher. (See Figure 32-1-12)

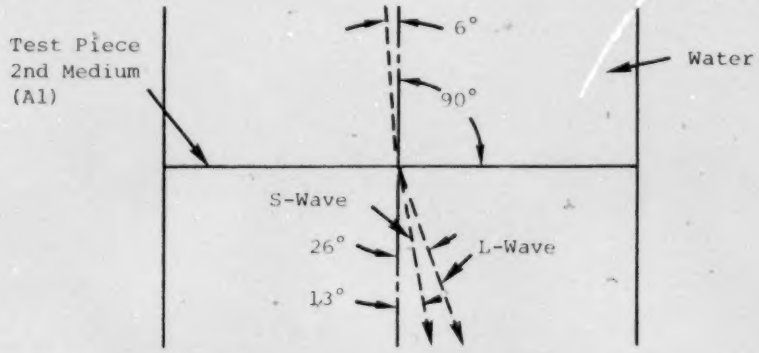


Figure 32-1-11. Illustration of Snell's Law

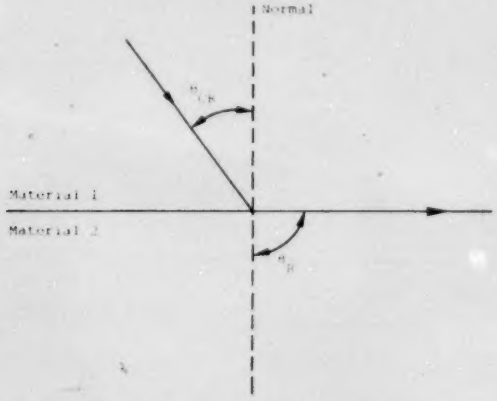


Figure 32-1-12. Critical Angle

EXAMPLE

Problem: What is the angle of refraction for: a) an L-wave, b) an S-wave?

Given: An ultrasonic wave in water is incident upon aluminum at 6° from the normal.

Solution:

$$\frac{\sin \theta_i}{\sin \theta_R} = \frac{C_1}{C_2} \text{ therefore, } \sin \theta_R = \frac{C_2}{C_1} \sin \theta_1$$

$\theta_1 = 6^{\circ}$ $\quad \sin \theta_1 = 0.105$

$C_1 = 1.48 \frac{km}{sec}$ $\quad C_{R\ell} = 6.30 \frac{km}{sec}$ $\quad C_{Rt} = 3.13 \frac{km}{sec}$

a) $\sin \theta_R = \frac{6.30}{1.48} \times 0.105 - 0.445$

$\theta_R = 26.4^{\circ}$ for L-wave

b) $\sin \theta_R = \frac{3.13}{1.48} \times 0.105 - 0.221$

$\theta_R = 1.27^{\circ}$ for S-wave

Critical Angles

Critical angle is the angle of incidence where sin θ refraction is unity. At the critical angle, a surface wave is propagated and above the critical angle, the ray is totally reflected.

Table 32-1-3. First Medium is H_2O[1]

Test Material	1st Critical Angle	2nd Critical Angle
Beryllium	7°	10°
Aluminum, 175T	14°	29°
Steel	15°	27°
Stainless, 302	15°	29°
Tungsten	17°	31°
Uranium	26°	51°

Table 32-1-4. First Medium is Plastic[1]

Test Material	1st Critical Angle	2nd Critical Angle
Beryllium	12°	18°
Aluminum, 175T	25°	59°
Steel	27°	56°
Stainless, 302	28°	59°
Tungsten	31°	68°

[1]Ultrasonic Testing, General Dynamics Convair Division, San Diego, California, 1967.

EXAMPLE: 32-1-5

Problem: What are the critical angles for L-waves and S-waves?

Given: Ultrasonic waves in water incident upon aluminum.

Solution:

For a critical angle, $\sin \theta_R = 1$, therefore

$$\sin \theta_i = 1 \times \frac{C_i}{C_R}$$

a) $$\sin \theta_{i_{CR}} = \frac{1.48}{6.30} = 0.235$$

$$\theta_{i_{CRIT}} = 13.6^{\circ} \text{ for L-waves}$$

This is called the first critical angle.

b) $$\sin \theta_{i_{CR}} = \frac{1.48}{3.13} = 0.0473$$

$$\theta_{i_{CRIT}} = 28.2^{\circ} \text{ for S-waves}$$

This is called the second critical angle.

Interference and Standing Waves

When two waves pass through each other, or superpose, their amplitudes add to each other at every point they overlap. This process is called interference. When two or more wave's amplitudes add in such a manner as to increase the resulting amplitude, the process is referred to as constructive interference. When two or more wave's amplitudes add in such a manner as to decrease the resulting amplitude, the process is referred to as destructive interference. Both, of course, may be present in one interaction. Figure 32-1-13 gives schematics of each case for pulses.

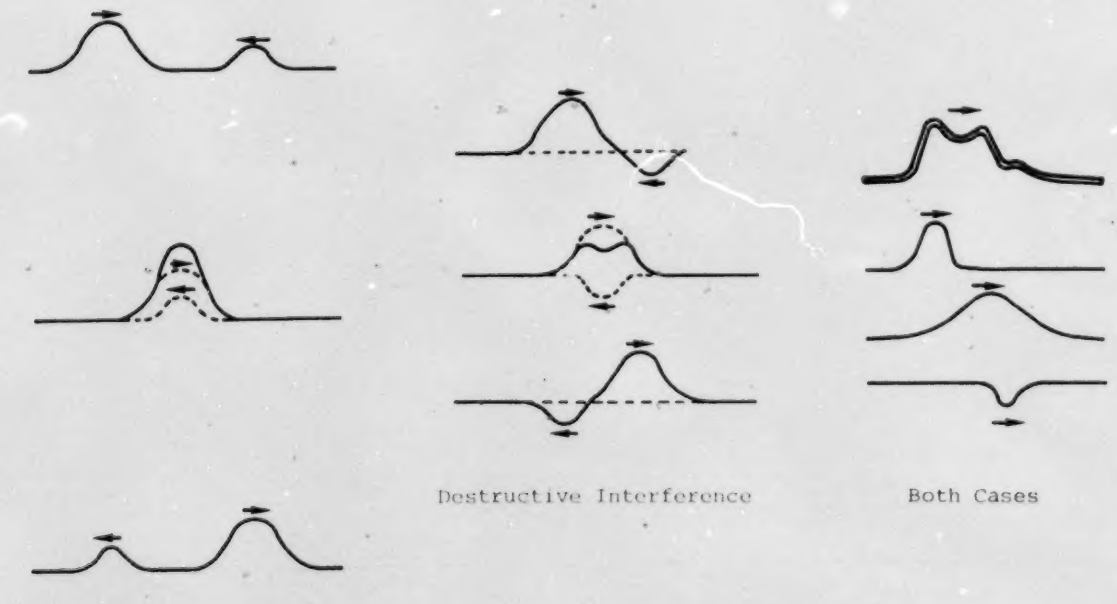


Figure 32-1-13. Superposition

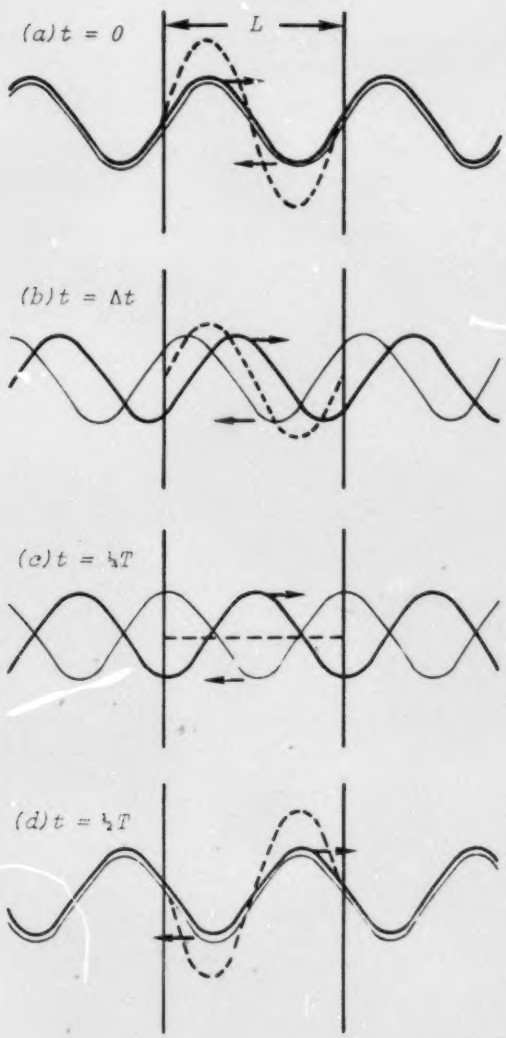


Figure 32-1-14. Standing Waves

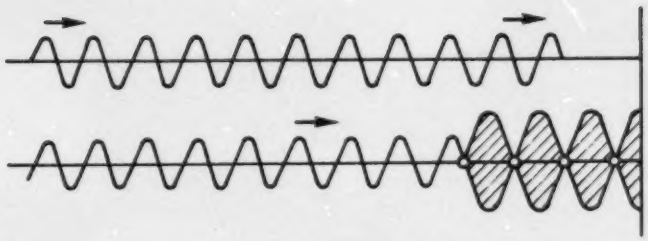


Figure 32-1-15. Standing Waves from a Free Wall

For long duration periodic waves of the same frequency, a very special phenomenon can occur for waves of the same frequency, amplitude, and direction of propagation: standing waves. In standing waves, the waves appear not to propagate but seem to oscillate in place. This is easiest to visualize in the special case of two waves propagating in exactly opposite directions.

When the two waves superpose, as in Figure 32-1-14, their amplitudes will add as previously discussed. However, at certain points called nodes, the addition will always be destructive. Between these points the waves will appear as single oscillations in place, with a maximum amplitude of twice either individual wave.

When a wave is reflected from a free boundary, one where the acoustic impedance is significantly less in the second material, the reflection occurs at an antinode. See Figure 32-1-15. A typical free boundary is the steel-air interface at the surface of a test sample (going from steel to air).

When a wave is reflected from a clamped boundary, one where the acoustic impedance is significantly greater in the second material, the reflection occurs at a node. See Figure 32-1-16.

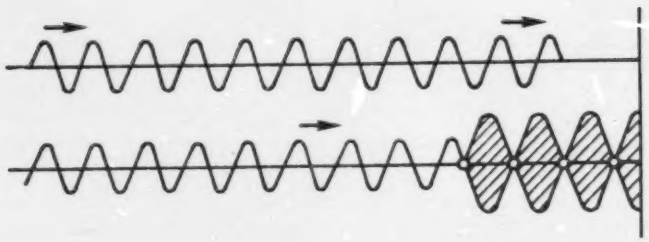


Figure 32-1-16. Standing Waves from a Fixed Wall

Standing waves are used in ultrasonic testing in resonance testing to measure wall thickness. Elsewhere, one should go to great lengths to avoid standing waves as they can be a major source of confusion and/or error.

Acoustic Impedence

The acoustic impedance determines what portion of acoustic energy incident upon an interface is reflected and what is transmitted. Sometimes, known as sound resistance, the acoustic impedance is defined as the product of a material's velocity of sound and its density.

$$Z = \rho c$$ Equation 32-1-6.

Z = Acoustic Impedance

ρ = Density

c = Velocity of Sound

The densities, velocities of sound, and acoustic impedances of some materials of interest are given in Table 32-1-5.

Table 32-1-5. Sonic Properties

Material	Density (gm/cm^3)	Velocity of Sound ($\frac{km}{sec}$)	Acoustic Impedance (gm/cm^2 -sec)
Steel	7.85	5.90	4.63
Aluminum	2.71	6.30	1.72
Water	1.00	1.48	0.148
Air	0.00129	0.33	0.00004

The fraction of the incident wave's energy reflected for an incident angle of 0° (normal) is given by the formula:

$$R = \left(\frac{Z_2 - Z_1}{Z_2 \quad Z_1} \right)^2$$ Equation 32-1-7

The reflection coefficient (R) is the ratio of the reflected and incident beam intensities.

Where:

R = reflection coefficient

Z = Acoustic impedance

The fraction of incident energy transmitted for normal incidence is given by:

$$T = \frac{4Z_2Z_1}{(Z_2 + Z_1)^2}$$ Note: $R + T = 1$ Equation 32-1-8

Where:

T = Transmission Coefficient

Z = Acoustic Impedance

The transmission coefficient (T) is the ratio of the transmitted and incident beam intensities.

EXAMPLE: 32-1-6

Problem: Find R and T

Given: A steel - aluminum interface.

Solution:

$Z_{Al} = 1.72 \qquad Z_{St} = 4.63$

$$R = \left(\frac{4.63 - 1.72}{4.63 + 1.72}\right)^2 = \left(\frac{2.91}{6.35}\right)^2 = \left(\frac{2.91}{6.35}\right)^2 = 0.46^2 = 0.21$$

$$T = \frac{4 \times 4.63 \times 1.72}{6.35^2} = \frac{31.82}{40.32} = 0.79$$

Beam Spreading

Compared to audible sound, ultrasound spreads very little while propagating through matter. Since the divergence of a wave beam is dependent upon wavelength, i.e., a short wavelength diverges very slowly, the shorter wavelengths or higher frequencies approach very closely to a straight-sided projection of the side of the transducer. In reality, however, there is always some spreading of the beam.

If the diameter of the transducer is given by D, the beam begins to spread at a distance $D^2/4\lambda$ from the transducer. Out to this distance the ultrasonic beam is said to be in the "near field", beyond, it is in the "far field". The far field appears to be a cone with its vertex at the center of the transducer face. See Figure 32-1-17 on the following page.

The rate of spread in the far field can be calculated from the formula:

$$\sin \frac{\theta}{2} = 1.22 \left(\frac{\lambda}{D}\right) \qquad \text{Equation 32-1-9}$$

Where:

θ = Vertex angle of the far field cone.

λ = Wavelength

D = Diameter of Probe Face

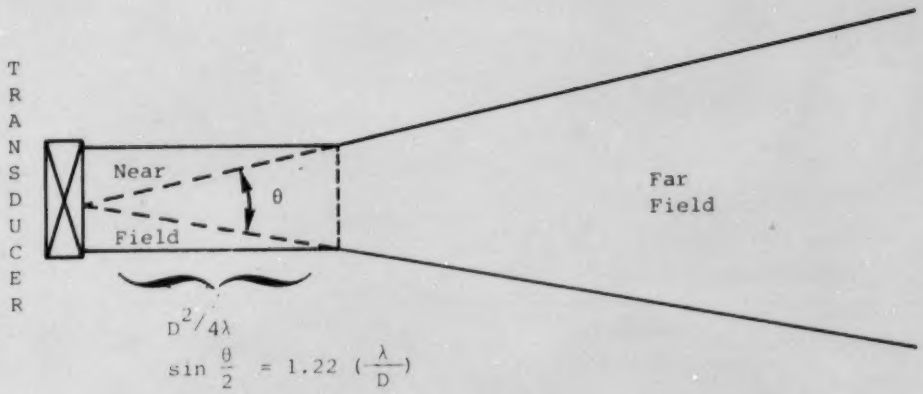


Figure 32-1-17. Ultrasonic Beam Spreading

EXAMPLE: 32-1-7

Problem: What is the length of the near field?

Given: A:2 MHz UT procedure in steel with a 1 inch probe.

Solution: $L = \frac{D^2}{4\lambda} = \frac{(25.4mm)^2}{4 \times 2.9mm}$

$L = 54.6\ mm = 5.46cm = 2.1\ in.$

EXAMPLE: 32-1-8

Problem: What is the half-angle spread for the far field?

Given: Same as Example 32-1-7.

Solution: $\frac{\theta}{2} = \sin^{-1}(1.22 \frac{\lambda}{D}) = \sin^{-1}(1.22 \times 2.9/25.4)$

$\frac{\theta}{2} = \sin^{-1}(0.14) = 8.0^{\circ}$

Table 32-1-6. Beam Spread in Steel = $\frac{\theta}{2}$

$C\ell = 5900 \frac{m}{sec}$		Transducer Diameter (in.)			
Frequency (MHz)	λ(mm)	3/8	1/2	3/4	1
0.50	11.8	~*	~*	49.1°	34.5°
1.00	5.9	49.1°	34.5°	22.2°	16.5°
5.00	1.2	8.7°	6.5°	4.3°	3.2°
15.00	0.4	2.9°	2.2°	1.4°	1.1°

*D must be larger than λ to use this formula, and 1/2 in. = 12.7mm, therefore, 3/4 in. is the minimum diameter for the formula.

Table 32-1-6 shows the dependence of beam spreading upon frequency and transducer diameter. By increasing either, you may reduce beam spread, but it should be noted that there other considerations than spreading which may be affected by changing frequency or beam diameter, such as attenuation and necessity to precisely locate a small flaw.

Attenuation

Attenuation of ultrasonic waves is due to two main mechanisms: scattering and absorption. These two phenomena can be combined into the single concept of attenuation or extinction.

Scattering results from inhomogeneities in the material. The inhomogeneities may be either large or small scale. The large scale class includes pores and inclusions (impurities) and mixed crystalline structures (as in brass and steel). The small scale class essentially refers to the scattering of the waves off of the boundaries of the microscopic crystalline structure when the crystals are oriented randomly.

Absorption is the direct conversion of sound energy into heat. Several processes are involved, but since each is quite complicated they fall beyond the purpose of this module and will not be further treated. An approximate picture of absorption can be imagined if the wave oscillations are treated as being friction - braked, which causes them to die out and converts their energy to heat.

Both processes affect the ultrasonic testing process. Pure absorption merely weakens all signals and is easily remedied. You only have to increase the amplitude output of the receiver-amplifier. Scattering introduces spurious echoes or noises, which must either be ignored or electronically suppressed. Both types of attenuation increase with frequency, making the attenuation losses for a 12 MHz signal much greater than for a 1 MHz signal.

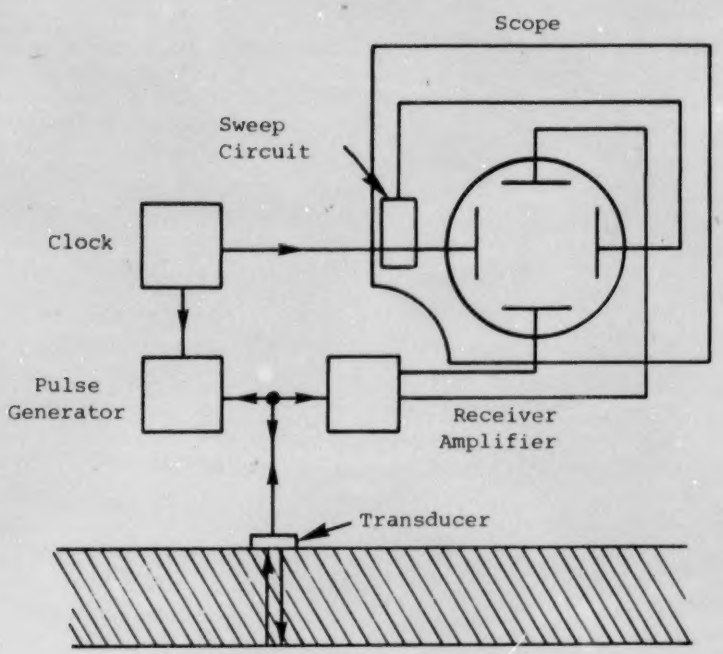
ULTRASONIC TEST EQUIPMENT

Basic Equipment

Each manufacturer of ultrasonic test equipment builds in features that are peculiar to that particular brand, but all general purpose units are, in broad terms, fairly similar. The usual way to break a unit into components is by function: the power supply, pulse generator, receiver-amplifier, clock, oscilloscope, and transducer assembly or probe. This description is for an A-scan pulse echo instrument which is, by an extremely large margin, the most common ultrasonic test equipment in use.

The power supply provides the energy to each of the other components of the instrument. It usually draws on 120V or 240V AC line power, although many portable instruments are battery driven.

The pulse generator or pulser, produces an electronic pulse at the desired frequency when triggered by the clock. The primary frequency, the pulse duration, the profile of the pulse envelope, and the pulse repetition rate may or may not be variable. This pulse is then transmitted to the probe.



Power supply not shown.

Figure 32-1-18 A-Scan Test Setup

The receiver-amplifier takes the return signal from the probe and amplifies it and otherwise processes it for display or data processing. The output signal from the receiver is customarily fed into an oscilloscope.

The oscilloscope displays the signal from the receiver amplifier in one of two modes: RF (radio-frequency) mode or video mode. The oscilloscope gives complete waveforms in the RF mode, but only peak intensities are shown in video mode. Some units operate on only RF or video while others allow for selection of either by the operator.

The clock is an electronic device which produces logic pulses and reference voltages and waveforms. These pulses, voltages, and waveforms serve to coordinate the operation of the instrument.

The probe has a transducer as its main component. A transducer either mechanically vibrates in response to an applied voltage, or produces a voltage in response to an applied mechanical vibration. The former is a sending transducer and the latter a receiving transducer. Transducers will be more completely discussed in a later section. Included in the probe unit will be cables, a housing, and a damping material affixed to the transducer.

Typical Controls

While different manufacturers of ultrasonic test equipment all have at least slightly different control setups, there are at the same time enough similiarities in basic functions that wildly divergent versions are not too common. Therefore, an introduction to the basic panel of a simple unit, as pictured in Figure 32-1-19 is in order.

The power supply is virtually always controlled by switch(es), frequently built into a rheostat controlling some other function, such as grid illumination. The power supply may also have a built-in time delay to protect the rest of the instrument during warm-up and will itself be protected by fuses.

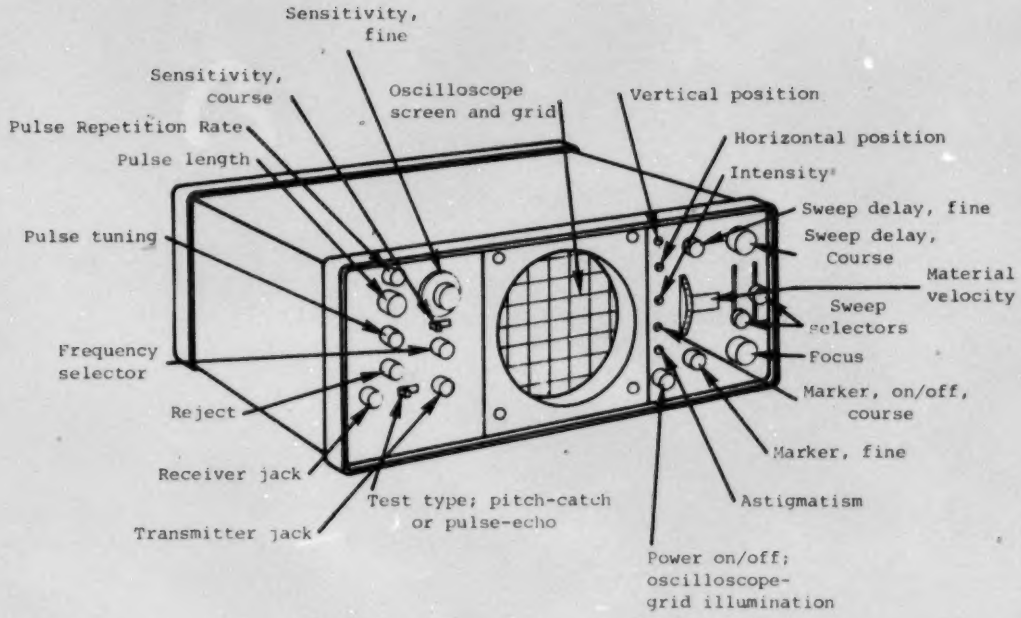


Figure 32-1-19. Typical pulse-echo instrument

The controls for pulse manipulation adjust the pulse repetition rate, the pulse length and pulse tuning or envelope shaping. The principle pulse frequency range is selected by a knob marked frequency.

The transducer cable(s) is(are) connected to the unit through the T (or transmitter) jack for single transducer procedures and through the T and R (or receiver) jacks for two transducer procedures. Which configuration is active is controlled by a selector switch which is usually labeled test-type.

The receiver-amplifier's gain is controlled by a single switch or a pair of switches marked sensitivity. The two switch set-up is usually a division by degree, into coarse and fine sensitivity.

With the exception of timing functions and grid illumination, most of the oscilloscope controls are usually of the set screw type as they require only infrequent adjustment. The set screw controls are:

- Vertical position
- Horizontal position
- Brightness
- Focus
- Astigmatism

The timing controls adjust sweep rate and delay time controls. The sweep delay time is used to position the initial pulse on the screen. The sweep delay can be used to eliminate water transmission times in immersion testing.

The sweep rate adjusts the length of the horizontal sweep or baseline moving signals to the right of your starting point. The grid illumination control frequently includes the main power switch.

There are several controls which may be present on the more sophisticated apparatus, such as mode selection, switch, marker circuit controls, driving voltage selector and gated alarm units. The mode selection switch allows the selection of either RF or video modes. If a marker circuit is included, there will be an on/off switch and a frequency selection. The driving voltage selector matches the output of the pulse generator to special transducers. The gates alarm units, which trigger visible, audible, or electronic alarms upon detection of a flaw in a specific region of the test material, generally have three controls. They are leading edge or beginning of gate position, width of gate or trailing

edge of end of gate position, and a threshold or sensitivity control which sets the minimum return signal height to trigger the alarm.

Transducers

Virtually all ultrasound transducers are piezoelectric devices, with the exception of a few low frequency devices used to test materials such as concrete and rock which will not be covered in this module. Piezoelectric materials have two basic properties that are of interest to the ultrasonic test technician. The first is the direct piezoelectric effect and the second the inverse piezoelectric effect. The direct effect is used in detecting mechanical vibrations, the inverse effect in producing mechanical vibrations. The name piezoelectricity is from the Greek for "pressure electricity".

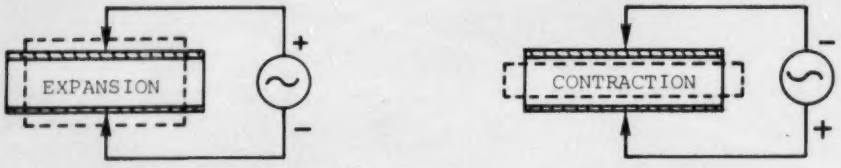


Figure 32-1-20 Piezoelectric Effect

As the name implies, a piezoelectric material develops an electric charge on its surface when deformed by an external mechanical force. This physical principle was discovered in 1880. By 1881, the inverse piezoelectric effect was discovered wherein the application of an external electric field causes a piezoelectric material to deform.

The most important transducer materials are quartz (SiO_2) first, followed by lithium sulfate ($LiSO_4$), barium titanate ($BaTiO_3$), and lead metaniobate ($PbNb_2O_6$). The first two are natural piezoelectric crystals, the second pair consists of polarized, or artificially made piezoelectric materials. There are other materials intended for special applications, but the four listed above are far and away the most commonly used.

The oldest piezoelectric material, quartz is chemically resistant and very hard, being slightly harder than tempered steel. All the other piezoelectric materials are much less chemically resistant. Quartz also has the advantage of only needing a back surface contact, the face of the metal being tested can be the front surface contact.

Barium titanate is the best transmitter material, and lithium sulfate is the best receiver material if viewed only in terms of the size of mechanical oscillations possible to the crystals, but lead metaniobate matches the sound transmission of most test materials well and can produce very short pulses making it the best all around material, excepting a lack of durability when compared to quartz, for ultrasonic testing.

Physically, a transducer consists of an active element or crystal, a damping body, and the housing. The crystal is the piezoelectric material and has a metallic coating on its front and back surfaces to act as electrodes.

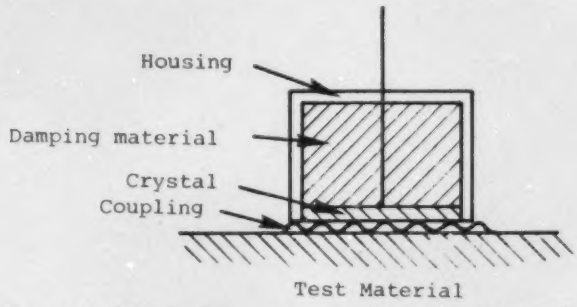


Figure 32-1-21 Transducer or Probe

The thickness of the crystal is not extremely critical, but for most efficient operation, a crystal should oscillate at its fundamental frequency. The fundamental frequency at which any substance can vibrate is the frequency corresponding to a wavelength equal to twice its thickness.

$$d = \frac{\lambda}{2} = \frac{1}{2}\,\frac{c}{f} \qquad \text{Eq 32-1-10}$$

Where

d = thickness

λ = wavelength

c = velocity

f = frequency

EXAMPLE: 32-1-9

Problem: What thickness(es) must a quartz plate have to oscillate at the following frequencies?

Given: (a) 2 kHz (b) 2 MHz

$C = 5.76 \frac{km}{sec}$

Solution:

(a) $d = \frac{\lambda}{2} = \frac{1}{2}\frac{c}{f} = \frac{1}{2}\frac{5.76 \text{ km/sec}}{0.002 \text{ MH}_2} = 1.44(10)^3\text{mm}$
$= 1.44\text{m}$

(b) $d = \frac{1}{2}\frac{c}{f} = \frac{1}{2} \times \frac{5.76}{2} = 1.44\text{mm}$

A piezoelectric crystal can be excited to its fundamental frequency by applying to its surface electrode an AC potential at that frequency.

The damping block may serve several functions. Most importantly, of course, the damping block "damps out" or rapidly attenuates the oscillations of the crystal in order to permit very short oscillations of the crystal. The damping block should also absorb the back surface waves along with any other waves entering it to avoid interference, especially with single probe operation. Also, it can supply mechanical support to thin crystals.

Not all transducers have integral damping. For pulses that are not especially short and a surface that is very smooth, the damping due to the coupling may be quite satisfactory. When tests are to be repeated frequently, a

crystal may be cemented directly to the test specimen, which will damp the crystal quite well.

The oscillator crystal and the damping block are normally fitted into a housing or casing which mechanically secures them in position. In addition, the housing electrically screens the crystal and for the unprotected quartz probes the casing provides the lead to the front surface electrode, i.e., the metal surface of the test material.

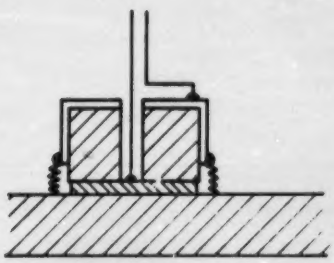


Figure 32-1-22 Electrical Connections to a Probe

The connecting cables are generally co-axial to shield the signals from ambient noise signals.

To get the signal from the transducer into the test material even very thin layers of air between them must be avoided. Since surfaces of materials are never perfectly flat a material, usually liquid, that is a better conductor of sound than air is used to "couple" the transducer and the test piece.

Couplants in common use include water, water plus glycerin, glycerin oils, petroleum and silicon greases, wallpaper paste, and very soft types of rubber. Separate couplants are, or course, not necessary for immersion testing.

Water, while a fair coupling agent, may have to be made wetter by the addition of a wetting agent such as glycerin to reduce its surface tension. Since glycerin has excellent acoustic properties, this may further improve the coupling.

The most frequently used couplant for contact tests is medium viscosity oil, grade SAE 20 or 30. This is especially true in testing steel in order to avoid corrosion as might be experienced with water. When testing non-horizontal or inverted surfaces, petroleum-based or silicon-based grease is recommended to avoid dripping. However, they are quite messy and expensive and wallpaper paste may be utilized instead, with soluble phosphates added to reduce corrosion.

Special Oscilloscope Notes

Since the oscilloscope is the basic means of presenting test data to the technician, he or she should understand how it operates. Oscilloscopes are divided into two classes or types depending on how they deflect the electron beams. The electromagnetic type uses magnetic fields to deflect the electrons and the electrostatic type uses electric fields. Only a few test oscilloscopes use electromagnetic deflection, most are electrostatic.

The heart of the oscilloscope is the cathode ray tube (CRT) which produces and directs electrons, causing them to trace out patterns on the fluorescent coating on the inside of its front surface causing it to glow.

The electrons are emitted from a heated cathode and accelerated by the anode(s) to speeds over 10^7 m/sec. These assemblies are frequently grouped together as the electron gun.

The deflection plates cause the stream of electrons to move both horizontally and vertically, there being a pair of plates oriented in each direction. The force of deflection is produced by the interaction of the electrons and the electric fields between the plates.

The vertical deflection is driven by the output of the receiver-amplifier with positive voltages being displayed upwards and negative downwards. The horizontal display is driven by the output of the sweep circuit, which in most ultrasonic test equipment is triggered by the clock. The waveform produced by the sweep is a "sawtooth" pattern sweeping the beam evenly across the screen, from left to right, and then providing a relatively rapid "flyback" or retract to restart the pattern, as seen in Figure 32-1-23.

This basic pattern is repeated frequently enough to provide a "continuous" trace just as motion pictures are successive photographs shown frequently enough to provide a continuous picture. In ultrasonic testing there will therefore be a horizontal line when no signal is being received by the receiver-amplifier. This horizontal line is known as the baseline. The length of the baseline is proportional to the length of time necessary to sweep from left to right.

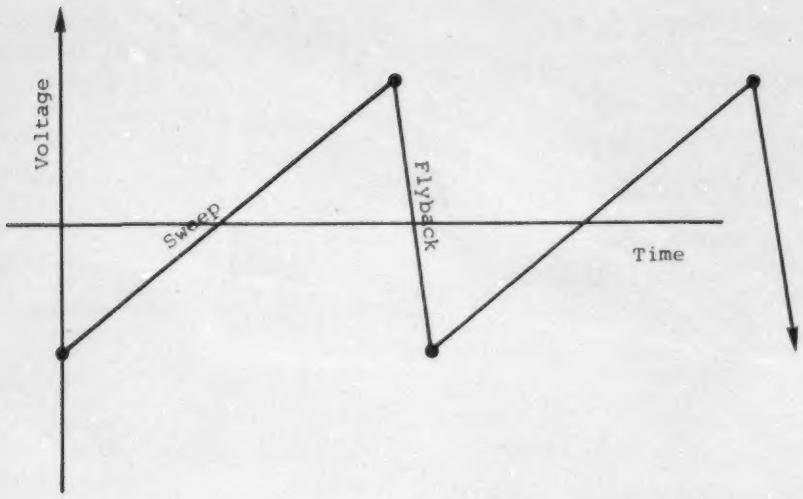


Figure 32-1-23 Sawtooth Voltage Waveform

Therefore, the distance along the baseline represents time which is proportional to distance travelled at a constant velocity. This enables an operator to adjust the horizontal sweep to a distance scale, so that distances in a material may be directly read on the face of the CRT.

If signal pulses are being received by the CRT, the vertical circuit will deflect the electron beam in such a way as to cause corresponding pulses or pips to appear on the screen. When reflection signals from the front surface, a discontinuity, and the back surface are displayed on the screen, the separation between them can be determined from their spacing on the screen. The section on testing will cover this in more detail.

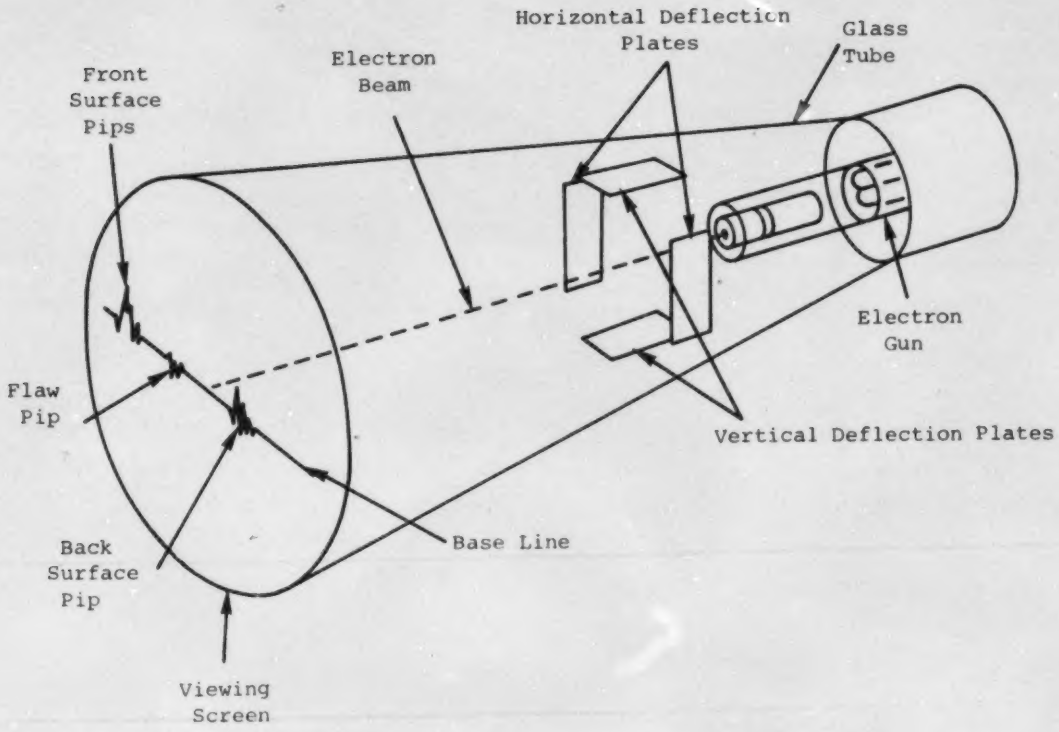


Figure 32-1-24 Typical Cathode-Ray Tube

TEST PROCEDURES

There are four (4) basic categories of procedures for ultrasonic testing if the procedures are being characterized by the variable being measured. Those categories are: resonant frequency method, intensity methods, transit time method, and intensity and transit time methods.

The resonance frequency method employs standing waves to measure sample thickness while the transit time method uses time of flight to measure thickness. The various intensity methods can be used to detect flaws but since no time measurements are made, no information about flaw depth can be obtained. The most comprehensive methods, and the most widely used, are the intensity and transit time methods. These can be used to locate flaws with precision.

Resonance Frequency

The resonance frequency method is the oldest non-destructive testing technique when you consider audible sound. Ceramics and metals were tested by listening to how the material "rang" when struck. There are sophisticated versions of this still in use, using complex electronics for excitation and analysis, but it has the drawback of only being able to detect large flaws at a size within approximately one order of magnitude of a wavelength of audible sound, which is several centimeters.

Ultrasonic resonance testing, however, can deal with quite small objects as the wavelength of ultrasound is much smaller than that of audible sound. The basic principle is the same as discussed in the previous section for crystal oscillations. Standing waves are set-up in a plate and their frequency used to calculate thickness by the formula.

$$d = \frac{1}{2} \frac{c}{f} \qquad \text{Eq 32-1-11}$$

Where

d = thickness
c = velocity
f = frequency

The problem with this approach is that it is very difficult to tell if a given standing wave pattern represents only a single half wavelength across the sample. The frequency associated with this wavelength is called the fundamental frequency.

Since other wavelengths are possible to standing wave patterns across a plate, it is therefore possible to have other frequencies. However, standing waves can exist only for thickness equal to an integral number of half wavelengths i.e.:

$$d = n\left(\frac{\lambda_n}{2}\right) \qquad \text{Eq 32-1-12}$$

Where

d = thickness
λ_n = wavelength
n = number of half wavelengths of wavelength λn.

Therefore, the thickness can be said to be equal to:

$$d = \frac{n}{2} \left(\frac{c}{f}\right) \qquad \text{Eq 32-1-13}$$

Where

d = thickness
n = number of half wavelengths
c = wave velocity
f = frequency

but you can't easily determine n.

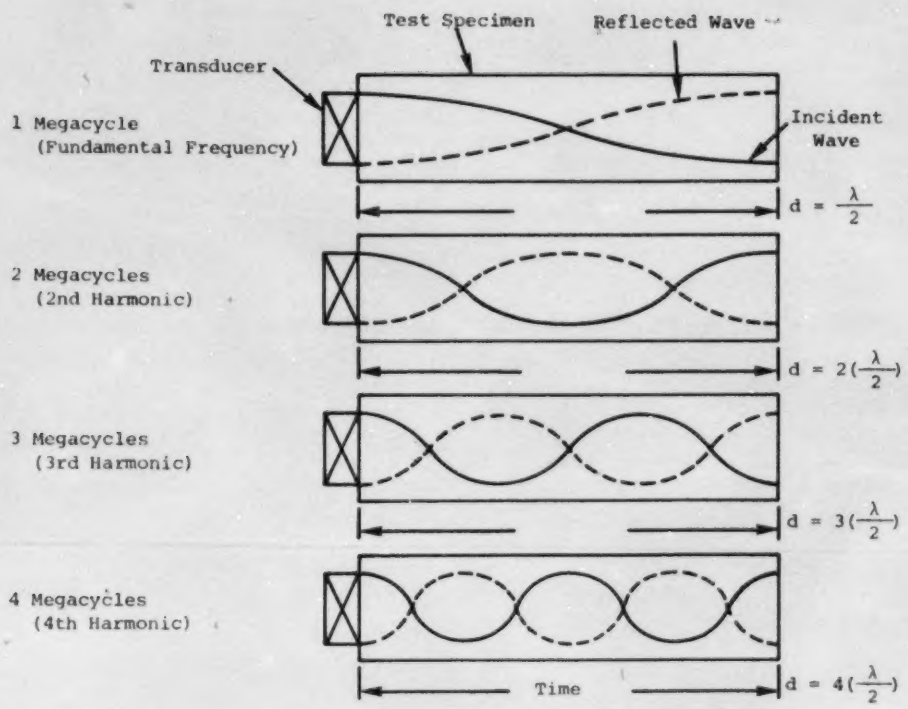


Figure 32-1-25. Standing Wave Patterns for Various Harmonics

There is one fairly easy approach to simplifying this, however. You can operate over a wide range of frequencies and measure when the transducer is resonating with the plate. The reason for this can be shown as follows:

$$\text{for any value of } \lambda_n,\ C = \lambda_n f_n \qquad \text{Eq 32-1-14}$$

Where

c = velocity

λ = wavelength

f = frequency

$$\text{and } f_n = \frac{C}{\lambda_n} = \frac{nc}{2d} \qquad \text{Eq 32-1-15}$$

Where

f = frequency
c = velocity
λ = wavelength
n = number of half wavelengths
d = thickness

$$\text{but therefore } f_1 = \frac{1c}{2d} \qquad \text{Eq 32-1-16}$$

$$\text{which implies that } f_n = nf_1 \qquad \text{Eq 32-1-17}$$

These frequencies called harmonics, overtones, or characteristic frequencies are equal to integral numbers of times the fundamental frequency and are therefore separated by just the fundamental frequency.

$$\Delta f = n\, f_1 - (n-1)\, f_1 = f_1 \qquad \text{Eq 32-1-18}$$

Where

Δf = difference in frequencies
f = frequency
n = number of half wavelengths

To find the fundamental frequency, in other words, one merely has to find any two adjacent harmonics of the plate by changing the frequency of plate oscillation by changing probe frequency. This is detectable because the transfer of energy between the probe and the plate is most efficient at the plate's characteristic frequencies, or when the probe's crystal is in resonance with the sample. The condition of resonance is, in this case, easily detectable as the power, or current drawn by the crystal will increase dramatically, or spike, as the driving frequency sweeps through the resonance frequency.

A serious problem with this method is the uniformity of the crystal's response to the driving voltage. If the

crystal is excited at one of its own characteristic frequencies, it will resonate with the driving circuitry and mimic a resonance with the plate. To avoid this, probes used in the resonance frequency test are always selected such that they will be excited below their fundamental frequency.

A second problem, that can not be so easily avoided, is the problem of coupling the probe to the test sample. The more efficient is the coupling between the probe and the test sample, as required for good sound transmission, the less independent is the response of the sample. The test sample and the probe become closely enough linked mechanically that they must be treated as one item responding to the oscillation, thus introducing an error by raising the resonant frequency. A way to reduce the relative error is to operate at as high a characteristic frequency as possible.

Once the fundamental frequency is known, thickness is easily found from Equation 32-1-19:

$$d = \frac{c}{2f_1} \qquad \text{Eq 32-1-19}$$

Where

d = thickness

c = velocity

f_1 = fundamental frequency

EXAMPLE: 32-1-10

Problem: Find the thickness of a sheet of aluminum using data from a resonance frequency test for process control.

Given: Harmonic peaks are detected at 2.03 MHz, 2.65 MHz, 3.26 MHz, and 3.84 MHz.

Solution: $f_1 = f_{n+1} - f_n = \Delta f_n$

$\Delta f_1 = 3.84 \text{ MHz} - 3.26 \text{ MHz} = 0.58 \text{ MHz}$

$\Delta f_2 = 3.26 \text{ MHz} - 2.65 \text{ MHz} = 0.61 \text{ MHz}$

$\Delta f_3 = 2.65 \text{ MHz} - 2.03 \text{ MHz} = 0.62 \text{ MHz}$

$f_1 = \overline{\Delta f} = 0.603 \text{ MHz}$

$$d = \frac{c}{2f_1} = \frac{6.30 \frac{\text{km}}{\text{sec}}}{2 \times 0.603 \text{ MHz}} = 5.22\text{mm} = 0.206 \text{ in.}$$

In practice, most test instruments in use today will directly display the thickness on an oscilloscope screen, generally by some form of overlay to the screen. A typical overlay is shown in Figure 32-1-26. The CRT screen itself displays frequency horizontally and peaks will therefore indicate the harmonic frequencies. To avoid confusion as to which harmonic is being displayed, at least two peaks are usually shown, as in Figure 32-1-26.

Figure 32-1-26 Overlay for oscilloscope for resonance frequency test.

When the overlay scale is correctly matched to the probe in use, generally by being color-coded or otherwise identically marked, each peak is read off its own scale. While each harmonic is by itself indistinguishable from others, the thickness can be read from the scales that match each other as in Figure 32-1-27.

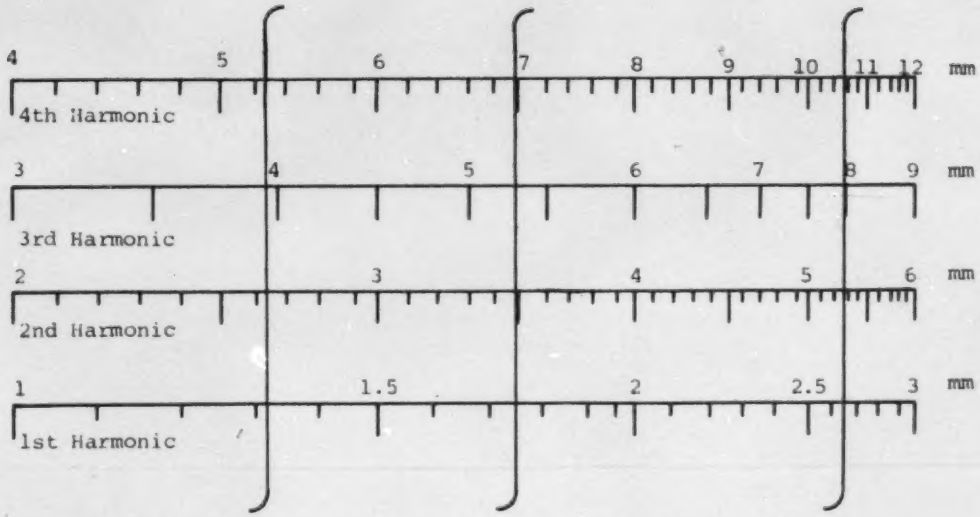


Figure 32-1-27 Oscilloscope display with overlay for resonance frequency test. The harmonics are the second and third and match at approximately 4:30 min.

EXAMPLE: 32-1-11

Problem: In a resonant frequency test for wall thickness of a pipe, how can the results be shown to be 4.30 mm?

Given: The display of Figure 32-1-27.

Solution: The first resonance peak intercepts the scales at 1.43 mm, 285 mm, 4.3 mm, and 5.7 mm.

The second peak intercepts the scales at 2.16 mm, 4.30 mm, 6.45 mm, and 8.3 mm.

The only match is at 4.3 mm, therefore, that is the thickness as measured.

When wall thickness measurements are made on smooth surfaces, sharp spikes or peaks are produced, but rough surfaces reduce the height of the resonances and smear them out over relatively wide bands of frequencies. This has two implications for actual testing. Firstly, it can be used as a testing method for checking the condition of inaccessible surfaces. Secondly, it means that great care must be taken to smooth the front surface by grinding and sanding.

One note about resonance frequency testing: if the sample has non-parallel sides, or an included flaw is inclined to the surfaces, the amplitudes of the resonant peaks may be reduced by any amount from a slight reduction to extinction.

Resonance testing uses many individual types of test instruments, both visual and audible data displays; many manufacturers and models; and even many different components for each model. As a result, all that can be reasonably said is that it is best to consult the manuals provided with each machine for operating details.

Intensity Method

The intensity method is actually a group of four techniques which measure the amplitude of ultrasound after propagation through a test piece. The four (4) techniques are the transmission method, reflection method, conduction method, and image projection method.

The first three(3) differ only in the positioning of the probes and/or the relative sizes of the test sample and the wavelength being used.

Transmission Method

The transmission method uses a high frequency generator to drive a transmitting probe which in turn continuously generates, ideally, plane waves propagating perpendicularly to the surface. After a single pass through the material, a receiving probe picks up the signal and passes it through to a receiver-amplifier which outputs to a gauge or some other instrument as shown in Figure 32-1-28. This is referred to as a continuous beam method. The receiving probe should be directly opposite to and aligned with the sending probe.

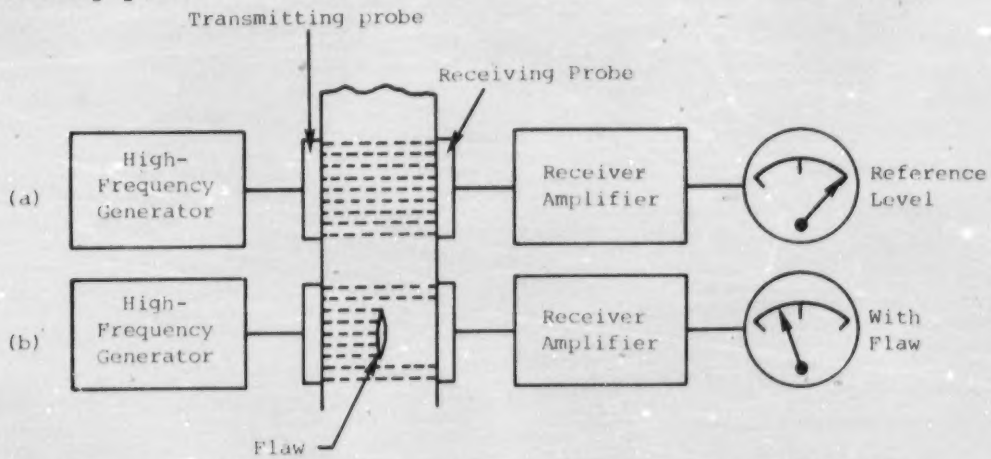


Figure 32-1-28 Intensity Method by Transmission

The signal through an unflawed region or test sample is used as a reference level. When a flaw blocks a portion of the beam, a signal reduction will be measured at the output gauge, indicating the presence of a discontinuity. The drawback to this method is that there is no way to determine the depth or orientation of the flaw.

Reflection Method

The reflection method uses an interface of the material to reflect a beam, usually back to the surface from which it was transmitted. In most other ways, it is identical to the transmission method. The most important difference is that the probes are angled to allow for separation of the receiver and transmitter. The probes are angled because this is a continuous wave method, and only pulsed methods can use the same transducer for transmission and reception.

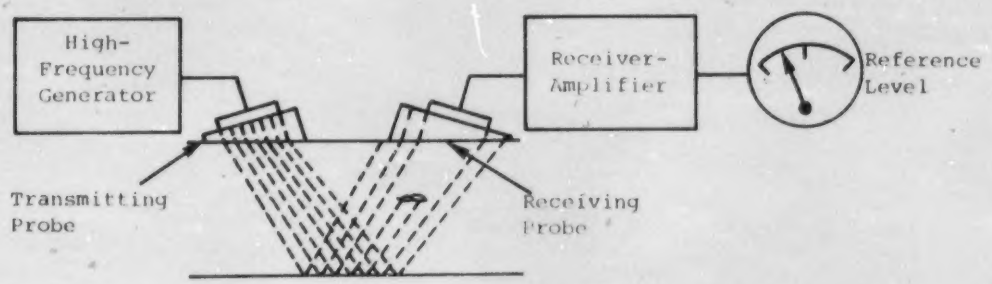


Figure 32-1-29 Intensity Method by Reflection

A major advantage of the reflection method, compared to the transmission method, is that only one accessible surface is needed.

Conduction Method

The third intensity method is the conduction method. The conduction method generally applies to small test samples, where the wavelength of the test signal is very large compared to at least one dimension of the test sample. Because of the relative sizes of the test sample and test

signal, there is no simple or "optical" path for the signal. There are reflections involved, of course, so this is closely related to the reflection method. And as in the reflection and transmission cases, the level of conduction in each case must be checked against some basis or reference level, which will be a similar test on an unflawed sample.

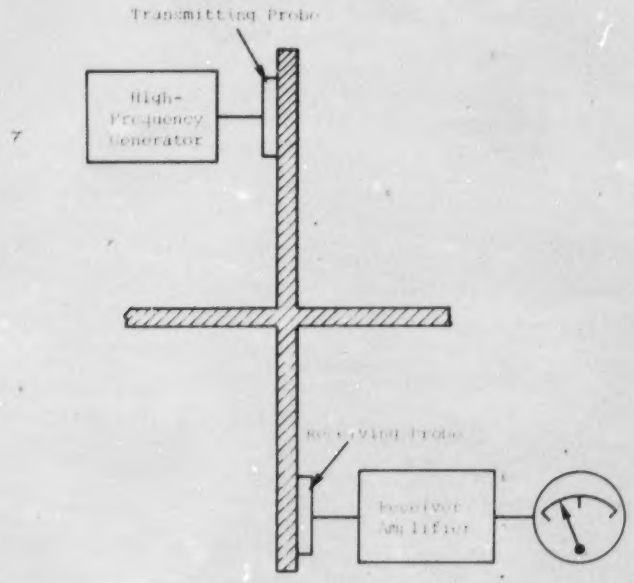


Figure 32-1-30 Intensity Method by Conduction

When dealing with continuous wave methods, as the intensity methods are, the test samples tend to become "filled up" with a three dimensional field of standing waves. Because no two test samples can ever be exactly alike, there will be widely varying patterns of nodes and anti-nodes in very similar appearing samples. Even a slight change of position (as small as one-half a wavelength) on an individual test sample can change received signal strength measurably.

In general wave propagation theory, there are two basic ways to break up this standing wave pattern. One is to change the entrance geometry of the waves as in the mode-mixing used in microwave ovens. The other is to quite rapidly vary or modulate the test frequency about some central value, thereby changing the wavelength and avoiding fixed patterns of standing waves.

The standing wave pattern can be smoothed out or "averaged" only if there is a path change of one-half wavelength over the modulation envelope. The required fractional change of frequency which is a function of frequency and plate thickness, can be very small for thick plates and therefore easily obtained, but can be very large for thin test samples. A large dynamic range is difficult to obtain in many transducers, which serves as a limit to the usefulness of this method.

The most important application of the intensity method is in the testing for laminar flaws in sheet metal by the transmission method. Also, it is best suited for automatically testing large numbers of identical (or nearly identical) test samples.

Intensity and Transit Time Methods

There are two types of intensity and transit time methods. The first type is the pulse transit time method, and the second is the frequency modulation method. The pulse transit time method may be split, as the intensity method was into transmission reflection, and conduction categories. The transmission and reflection methods along with the intensity method by transmission are the most

important methods in ultrasonic testing. Pulse transit time by reflection is the single most widely used method and is known as the pulse-echo method.

Pulse-Echo Method

The pulse-echo method, as its name implies, uses short pulses of ultrasound and therefore avoids the problem of exciting a standing wave field in a test piece. Another advantage of the pulses operation is that a single probe can both send and then receive between sending pulses.

The pulse-echo method works in the same manner as active sonar. It sends out a pulse of ultrasound which is reflected back to the receiver by either a discontinuity or the back wall. The size of the peak of a return echo is proportional to the echo's amplitude and contains information about the size of the reflecting surface or flaw. The other information contained in the echo is the depth of reflecting surface or flaw, and this can be determined from the equation:

$$d = c \cdot t \qquad \text{Eq 32-1-20}$$

Where

d = distance
c = velocity
t = time

The depth, of course, is equal to one-half the round-trip distance travelled by the pulse, so:

$$d = \frac{c \cdot t}{2} \text{ for depth} \qquad \text{Eq 32-1-21}$$

EXAMPLE: 32-1-13

Problem: Echoes for the flaw and the backwall are received during a pulse-echo test of steel plate. What is the approximate:

(a) flaw depth?
(b) wall thickness?

Given: t_{flaw} = 2 Msec, t_{bw} = 3Msec, c = 7000 $\frac{m}{sec}$?

Solution: (a) $d = \frac{1}{2}\ ct = \frac{1}{2} \times 7 \frac{km}{sec} \times 2\ \mu\ sec = \underline{7mm}$

(b) $d = \frac{1}{2}\ ct = \frac{1}{2} \times 7 \frac{km}{sec} \times 3\ \mu\ sec = \underline{10.5mm}$

A-Scan

The basic pulse echo scheme of data display is the so-called A-scan, using the oscilloscope to present pulse height versus time of flight. Figure 32-1-31 shows a schematic view of an A-scan.

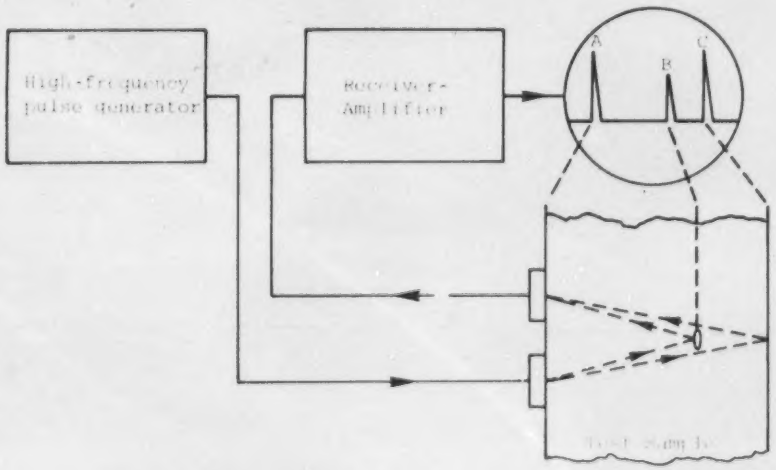


Figure 32-1-31 Pulse-echo Method, A-Scan.

The peak marked A in Figure 32-1-31, is the reflection off of the front surface of the test piece and is used as the reference for all time or depth measurements. The peak marked B is the reflection off of the flaw, and its amplitude is relatively small or inclined to the beam. In this case it is small. The peak marked C is the backwall echo and its position on the CRT corresponds to the thickness of the test object.

If the thickness of the test object is known beforehand, an A-scan device may be calibrated by setting the front surface and backwall peaks on grid lines on the CRT face and simply reading depths of intermediate echoes, flaws for instance, from the grid lines. If, however, thickness is not known, the device may be calibrated using test blocks or the internal marked circuitry, and then the thickness can be measured.

Measurement of the exact size of a flaw is not easily accomplished because the orientation, shape, depth, and nature of the flaw all affect its ability to reflect ultrasound. If a flaw is detected, more procedures may be employed to survey for size and orientation.

Some schematic views of typical A-scan data presentations are given in Figure 32-1-32. Part (a) shows the CRT display for the case of no detectable flaws in the test sample: there are only two peaks, the front surface and backwall echoes. The gap between these two peaks is, again, proportional to the object's thickness. Part (b) of Figure 32-1-32, shows the CRT display corresponding to a small flaw in the test piece. The peak due to the flaw appears in the same position relative to the front surface and backwall peaks that the flaw itself occupies with respect to the two surfaces.

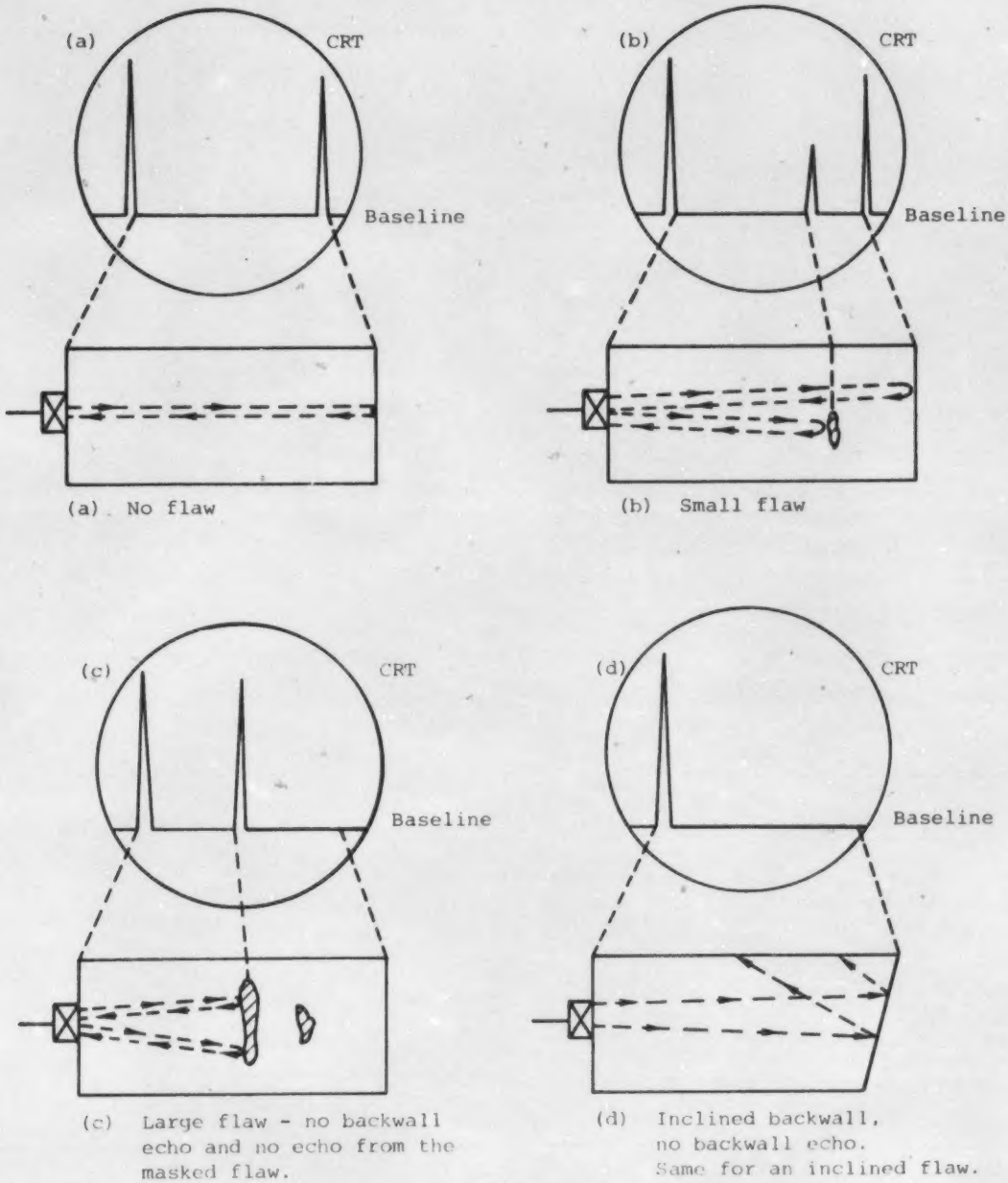


Figure 32-1-32 Schematic representations of typical A-scan data presentations in the pulse echo method.

Part (c) depicts the masking effect of a flaw larger than the beam and part (d) depicts the loss of signal due to the beam impinging upon an inclined surface. In this case it was the backwall, although it could have been an inclined flaw.

A test sample with parallel faces normal (or perpendicular) to the test beam shields multiple echoes, even without flaws, if the scale is set so that the first backwall echo is not on the right hand half of the screen. The additional echoes are due to multiple reflections off the surfaces of the test sample. The apparent positions of the additional wall can be seen in Figure 32-1-33 below. The heights of the echoes decrease because of an attenuation increase with increased path length and not all the incident beam is reflected at each interface. See Section on reflection and transmission coefficients.

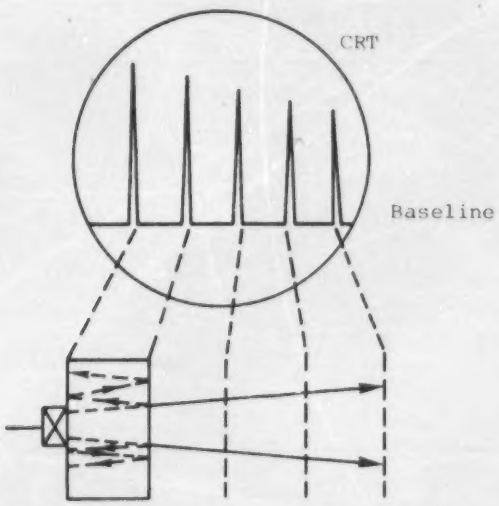


Figure 32-1-33 Multiple Echoes in a Flat Test Piece

The frequency at which these multiple echoes occur is referred to as the echo repetition frequency or the travel frequency and should not be confused with the pulse repetition frequency, which is the rate at which pulses are produced by the probe.

B-Scan

The B-scan version of the pulse-echo method uses the oscilloscope to display the elapsed time (vertically downwards) versus probe position (horizontally) as the probe is mechanically swept across the test piece. The oscilloscope itself will virtually always have a long persistence coating of phosphor to retain parts of the image already formed as the rest is swept out. The horizontal deflection will synchronize with the motion of the probe, which will normally be linear in direction and at constant speed. The intensity of the sweeps is modulated to represent the intensity of the echo, a bright segment indicating a strong echo.

The B-scan will therefore represent a "cross-section" of the tested material. This is the chief value or use of the B-scan. It can scan rapidly for the presence or distribution of flaws in a test piece and the results used to select where to scan more thoroughly using the A-scan method. The B-scan results may be recorded by facsimile or photographic equipment, or have the output data reproduced on an x-y plotter. Figure 32-1-34 shows a typical B-scan schematically.

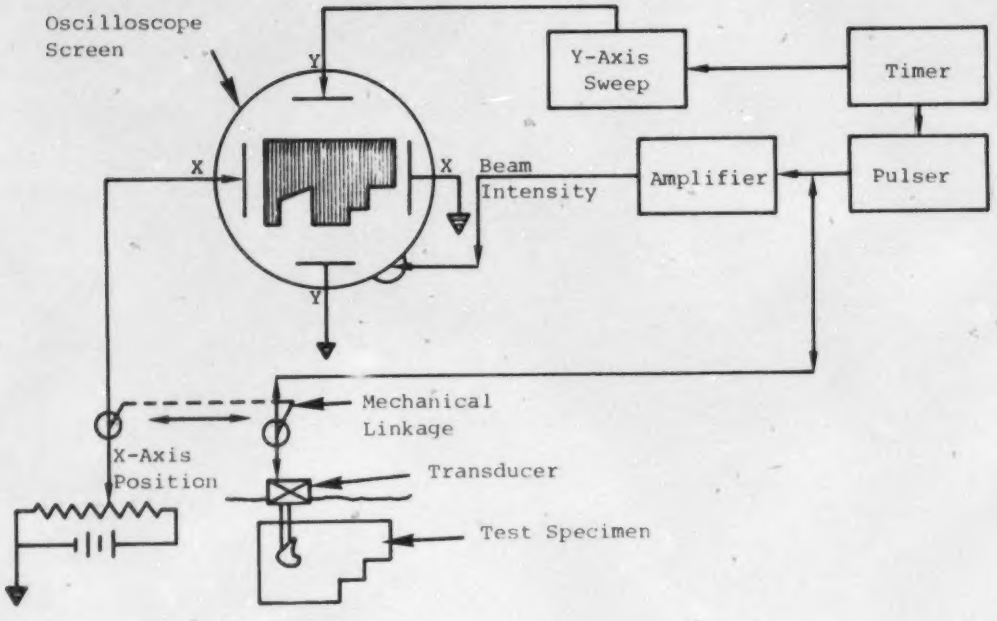


Figure 32-1-34 Schematic Representation of a B-scan test.

The B-scan "cross section" is generally set up with the top of the display representing the front surface and the bottom representing the backwall.

C-Scan

The C-scan is a two dimensional or planar view of the sample, displaying the positions of any detected discontinuities in the sample but no depth information. The probe is moved over the test sample in some kind of search pattern. The usual pattern is a series of parallel lines although zig zags and spirals are occasionally used. As in the B-scan, mechanical linkages are used to indicate the position of the probe to the x-y plotter.

The most important addition in the C-scan equipment, when compared to the B-scan, is the depth gate. This device allows only discontinuity signals from between two selected depths to be displayed. This allows you to reject the front surface and backwall echoes which would otherwise completely obscure the flaws. Generally, the gate will be set to just barely exclude the front surface and the back-wall from the display, but the gate can be used to display a series of sections or slices of the test item, which is the only way to get depth information by C-scan.

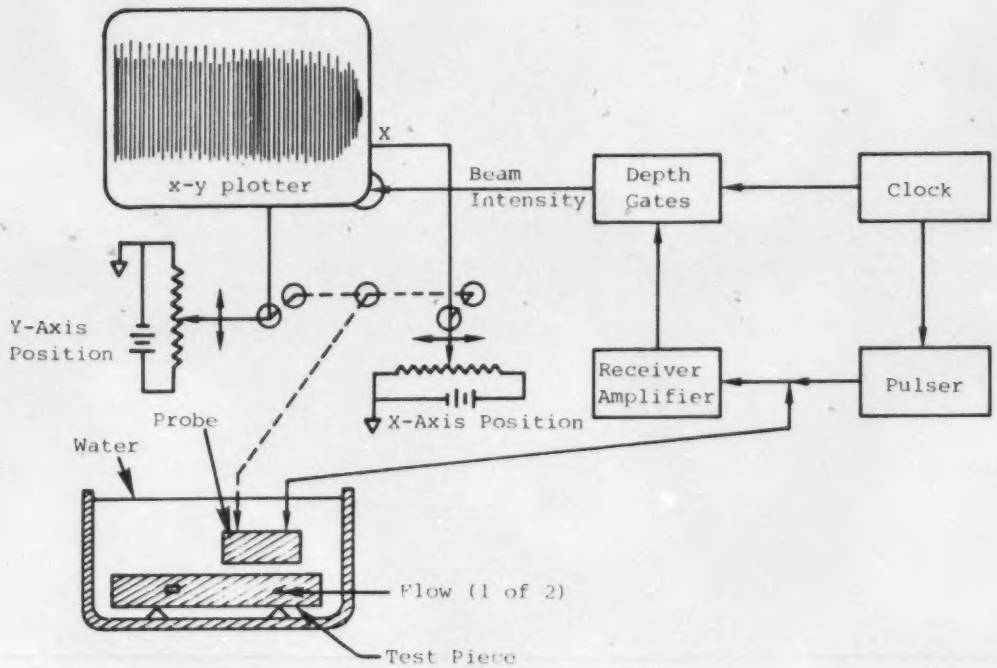


Figure 32-1-35 Schematic Diagram, C-Scan System for Pulse Echo Method

Figure 32-1-35 shows the schematic of a typical C-scan system as discussed above. Figure 32-1-36 shows a typical x-y plot obtained by C-scan with the flaws displayed as the light or blank areas. The opposite case is the flaws displayed as darkened regions. Both methods are common.

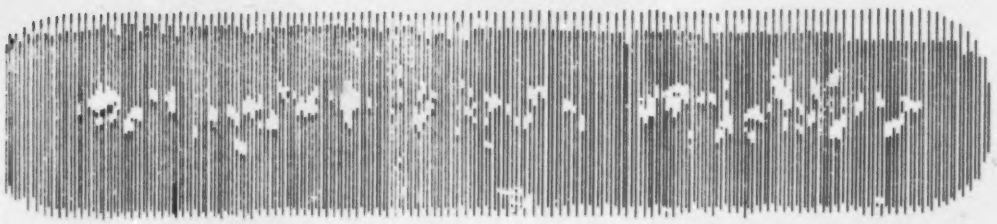


Figure 32-1-36 Typical C-Scan Recording

Transit Time Methods

In actuality, pure transit time methods have already been covered. All one has to do to make an intensity transit time method into a transit time method is to disregard intensity readings. A pulse-echo instrument may be converted to a transit time method merely by replacing the CRT with a digital readout for elapsed time.

The transit time method first used, as early as 1941, was the "sing-around" method. The returning echo triggers a second pulse, thereby making the pulse repetition frequency equal to the echo repetition frequency instead of being preset. The pulse repetition frequency can then be directly measured and the round trip period (T) of a pulse found by solving Eq 32-1-21 for period:

$$T = \frac{1}{f} \qquad \text{Eq 32-1-21}$$

Where:

T = period

f = frequency

The thickness or the depth of a flaw can be given by:

$$d = \frac{c \cdot T}{2} = \frac{c}{2f_r} \qquad \text{Eq 32-1-22}$$

Where:

d = thickness

c = velocity

f_r = pulse repetition frequency

The essential drawback to this method is that the triggering time of a pulse is a very difficult quantity to control, and generally speaking, it isn't as accurate as the pulse-echo method.

EXAMPLE: 1.13

Problem: What is the approximate thickness in inches of a steel plate for a particular pulse repetition frequency.

Given: f_r = 59 kHz

Solution: $d = \frac{c}{2f_r} = \frac{5.9 \text{ km/sec}}{2 \times 0.059 \text{ MHz}} = 50\text{mm}$ $\underline{\underline{d = \approx 2 \text{ in.}}}$

EXERCISES

The following exercises reinforce the concepts presented in this module.

1. Perform the Resonance Wall Thickness Method to measure a sample thickness as outlined in the Procedures section of this module.

2. Perform either a wall thickness measurement or a flaw detection by using the Pulse Echo Method as outlined in the Procedures section of this module.

3. Define the following terms:
   a. wavelength
   b. period
   c. frequency
   d. velocity
   e. acoustic impedance
   f. reflection
   g. refraction
   h. longitudinal wave
   i. transverse wave
   j. surface wave

4. Answer the following questions as either <u>true</u> or <u>false</u>:

____ a. The three basic parameters of a wave are its wavelength (λ), frequency (f), and velocity (v). Velocity is equal to the product of wavelength and frequency ($v = \lambda f$).

____ b. Two basic wave modes used in UT are longitudinal and transverse waves. Surface and plate waves are less frequently utilized.

____ c. The angle of reflection equals the angle of incidence ($\theta i = \theta r$), when an ultrasonic wave is reflected from an internal flaw.

____ d. When an ultransonic wave is refracted at an interface, the relationship between the angle of incidence and angle of refraction is given by Boyle's Law.

____ e. When an ultrasonic wave is refracted, the incident wave is split into L-wave and S-wave refracted waves.

____ f. When the critical angle of incidence is passed, total internal refraction occurs.

5. Identify and describe the following components and their functions for a typical ultrasonic test setup: probe, signal generator, receiver, cathode ray tube, amplifier, clock, and power supply.

6. Identify the type and purpose of an ultrasonic test given a schematic diagram of the test setup.

7. Answer the following questions as either <u>true</u> or <u>false</u>:

____ a. The basic components of an ultrasonic test unit are: the power supply, pulser, receiver-amplifier, clock ocsilloscope, and probe (A-Scan setup).

____ b. Transducers are ferromagnetic devices.

____ c. The most common transducer material is quartz followed by lithium sulfate, barium titanate, and lead metaniobate. Quartz is very hard, lithium sulfate the best receiver, barium titanate the best transmitter, and lead metaniobate the best all around except it's soft.

____ d. A couplant, usually a molybdenum-base grease, is used to conduct the sound waves from the transducer to the test piece.

____ e. An x-y plotter is the best means of presenting UT data to a technician.

8. Identify and briefly describe, the test method which would accomplish a stated test requirement.

9. Name the four (4) basic wave modes discussed in this module and describe each.

10. Name the four (4) classes of ultrasonic test and describe each.

11. Name the three (3) types of pulse-echo tests and distinguish between them.

MATERIALS

To carry out Exercise #1 the following materials are required as shown in Figure 32-1-37 of the Procedures.

1. Ultrasonic transducer
2. High frequency generator with variable frequency
3. Signal amplifier
4. Sweep voltage generator
5. Oscilloscope
6. Aluminum plate or sheet whose thickness is to be measured.

To carry out Exercise #2 the following materials are required as shown in Figures 32-1-31 or 32-1-34 of this module.

1. Ultrasonic transducer(s)
2. Oscilloscope
3. Signal amplifier
4. Pulser
5. Timer
6. High frequency pulse generator
7. Steel test specimen with internal flaw
8. Steel test specimen with no internal flaws

PROCEDURES

The following procedures refer to Exercises 1, 2 and 3 of this module.

1. Resonance Wall Thickness Method

   Using the test procedure explained on pages 32-1-44 through 32-1-52, measure the thickness of a sheet of aluminum using the Resonance Wall Thickness method. It is suggested that the measurement be carried out using the transducer and oscilloscope described in this section of the module.

   The following sketch in Figure 32-1-37 shows the basic test set-up for the resonance method for measuring the wall thickness of any material.

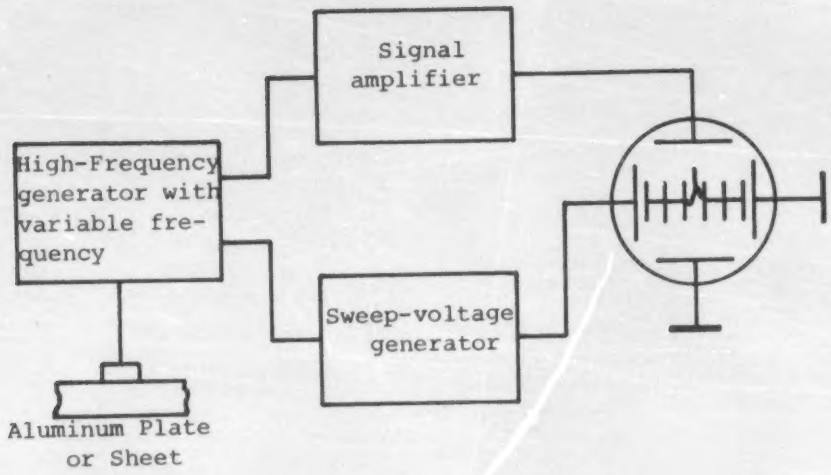


Figure 32-1-37 Test Set-up for Measurement of Wall Thickness through a Material

In the event that such equipment is not available, a field trip to an industrial site in which actual testing of this type is performed can be substituted. A report should be prepared on this aluminum sheet measurement:

a. List Title of Exercise.
b. Describe, very briefly, the method being used.
c. Read the manufacturers instruction manual and construct a block diagram similar to Figure 32-1-37 for the equipment involved.
d. Describe how the equipment is calibrated.
e. Describe the test piece.
f. Make the measurement(s) required to perform the test.
g. Record the results and with diagrams show how the measurement(s) was (were) made.

2. Pulse Echo Method

Using the test procedure outlined on pages 32-1-57 through 32-1-66 measure the wall thickness or the depth of an internal flaw using a test instrument set-up as shown in either Figures 32-1-31 32-1-34 of this module. These tests and measurements should be written up as shown below: with step f included for an actual laboratory or simulation and excluded for a demonstration or a field trip report.

a. List Title of Exercise.
b. Describe very briefly, the method being used.
c. Read the manufacturers instruction manual and construct a block diagram similar to Figure 32-1-31 or Figure 32-1-34 for the equipment involved.
d. Describe how the equipment is calibrated.
e. Describe the test piece.
f. Make the measurement(s) required to perform the test.
g. Record the results and with diagrams show how the measurement(s) was (were) made.

DATA TABLE

Not applicable.

REFERENCE MATERIALS

General Dynamics, Convair Division; Classroom Training Handbook for Nondestructive Testing: Ultrasonic Testing; General Dynamics; San Diego, California; 1967.

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Ward, Raymond, et al; Metals Handbook, 8th Edition, Volume 11, "Nondestructive Inspection and Quality Control;" American Society for Metals; Metals Park, Ohio, 1976.

TEST

Principles of Ultrasonic Wave Behavior

1. The boundary between two materials in contact with each other is called a(n) _____.
   (a) lens
   (b) interface
   (c) focuser
   (d) attenuator

2. The speed of propagation of a wave is also called its _____.

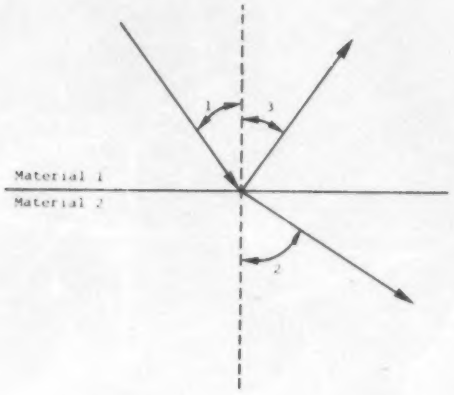

Figure 32-1-A

Questions 3 through 5 refer to these answers:
(a) angle of incidence
(b) angle of reflection
(c) angle of refraction
(d) none of the above

3. In Figure A angle 1 is called the _____.

4. In Figure A angle 2 is called the _____.

5. In Figure A angle 3 is called the _____.

6. Most ultrasonic testing is done between:
   (a) 1-25 megahertz
   (b) 25-100 megahertz
   (c) 1-25 kilohertz
   (d) 25-100 kilohertz

7. The formula $\frac{\sin \theta_1}{\sin \theta_2} = \frac{V_1}{V_2}$ is known as:
   (a) Snell's Law
   (b) Huygen's Principle
   (c) Phase conversion formula
   (d) Impedence Formula

8. In Figure A, assuming no mode conversion, which two angles are always equal?
   (a) Angles 1 and 3
   (b) Angles 2 and 3
   (c) None of these

9. The velocity of sound is highest in:
   (a) aluminum
   (b) air
   (c) water
   (d) steel

10. The point in a wave pattern where destructive interference cancels all apparent wave motion is called a:
   (a) compression
   (b) rarefaction
   (c) antinode
   (d) node

11. The product of _____ and _____ equals the velocity of a wave.

12. What is the wavelength of:
    (a) a 1 MHz longitudinal wave in aluminum?
    (b) a 5 MHz transverse wave in steel?

13. An longitudinal ultrasonic wave in water is incident upon steel at 10°, and is partly transmitted with mode conversion. What is the:
    (a) angle of reflection?
    (b) angle of refraction for the L-wave?
    (c) angle of refraction for the S-wave?

14. For a 2 MHz signal in steel, with a 1/2 in. transducer, what is the length of the near field and at what half angle does the far field spread?

15. Sketch the rays in problem 13, showing the correct angles approximately.

16. A material used between a probe and the test material to improve the transmission of ultrasonic waves is called the _____.
    (a) wetting agent
    (b) damping block
    (c) crystal
    (d) couplant

17. The piezoelectric material in a probe or search unit is called the _____.
    (l) housing
    (b) damping block
    (c) crystal
    (d) couplant

18. A scale electronically imposed on the screen of a CRT in a test unit to permit rapid measurement of distance may be referred to as _____.

(a) baseline
(b) pip
(c) sweep
(d) marker

19. A disadvantage of using a quartz probe is that it _____.

(a) will dissolve in water
(b) is an inefficient ultrasonic generator
(c) wears quickly
(d) needs special couplants

20. On many test instruments, while conducting an immersion test, it is possible to remove the portion of the pattern representing water by adjusting the _____.

(a) pulse length control
(b) reject control
(c) sweep delay control
(d) sweep length control

21. The transducer most frequently found in ultrasonic probes utilize _____.

(a) magnetostrictive principles
(b) piezoelectric principles
(c) mode conversion principles
(d) none of the above

22. Which material is the best ultrasonic transmitter?
    (a) lithium sulfate
    (b) barium titantate
    (c) quartz
    (d) silver oxide

23. Which material is the best ultrasonic receiver?
    (a) lithium sulfate
    (b) barium titanate
    (c) quartz
    (d) silver oxide

24. Which material wears best?
    (a) lithium sulfate
    (b) barium titanate
    (c) quartz
    (d) silver oxide

25. In the typical instrument described in this section, the clock controls the _____.
    (a) pulse length
    (b) amplification
    (c) pulse repetition rate
    (d) sweep length

26. Identify and describe the purpose of each of the six major components of an ultrasonic test assembly.

27. How thick must a quartz plate be to oscillate most efficiently at 15 MHz?

28. Describe the difference(s) between video and RF modes.

29. State the three (3) basic purposes that damping blocks fulfill in a transducer.

30. The vertical deflection on a test instrument CRT is driven by the output of the _____. The horizontal by the output of _____.

31. A form of thickness measurement testing in which ultrasonic vibrations of varying frequency are introduced into the test piece is called:
    (a) pulse echo method
    (b) intensity method
    (c) resonance method
    (d) immersion testing

32. In resonance testing, the resonant peaks may be obtained at either the fundamental frequency or at _____ which are the upper harmonics.
    (a) multiple reflections
    (b) overtones
    (c) nodes
    (d) anti-nodes

33. In _____ ultrasonic waves are transmitted into the test sample as short and repetitive wave packets.

(a) pulse echo testing
(b) continuous wave testing
(c) resonance testing
(d) all of the above

34. In Figure 32-1-B, showing a typical resonance device display, what thickness is indicated?

(a) 7.00mm
(b) 1.75mm
(c) 8.00mm
(d) 5.25mm

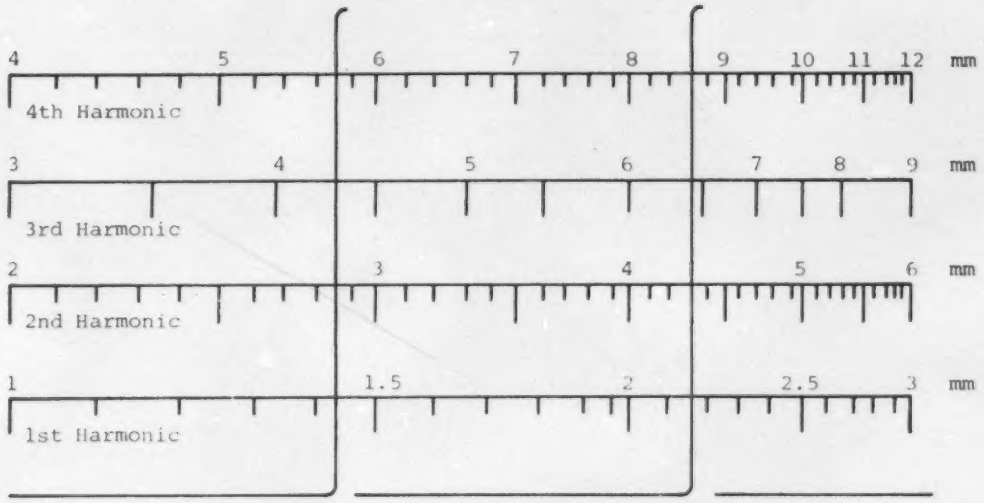

Figure 32-1-B

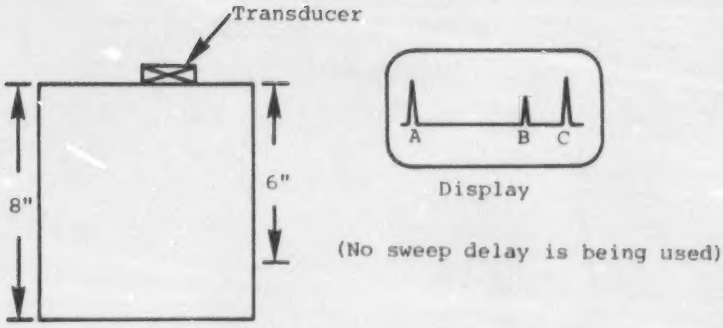

Figure 32-1-C

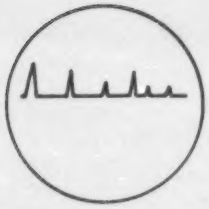

Figure 32-1-D

Figure 32-1-E

Figure 32-1-F

35. In Figure 32-1-C, what does display peak A represent?

(a) front surface
(b) flaw
(c) backwall
(d) none of the above

36. In Figure 32-1-C, what does display peak B represent?

(a) front surface
(b) flaw
(c) backwall
(d) none of the above

37. In Figure 32-1-C, what does display peak C represent?

(a) first backwall reflection
(b) second backwall reflection
(c) first flaw reflection
(d) second flaw reflection

38. Figure 32-1-D is a typical _____.

(a) A-scan
(b) B-scan
(c) C-scan
(d) D-scan

39. Figure 32-1-E is a typical _____.

(a) A-scan
(b) B-scan
(c) C-scan
(d) D-scan

40. Figure 32-1-F is a typical _____.

(a) A-scan
(b) B-scan
(c) C-scan
(d) D-scan

41. List the four types of methods of ultrasonic testing discussed and state which type(s) can be used to determine: (a) wall thickness
(b) flaw presence
(c) flaw location

42. List the four types of intensity method testing and distinguish between them on the basis of sound transmission.

43. List the three display schemes in pulse-echo testing and for each list the variables or quantities displayed on the axes of the display.

44. State the reason that requires reflection intensity testing to use two probes.

45. Distinguish between phosphor coatings on CRT's in A-scan and B-scan instruments.